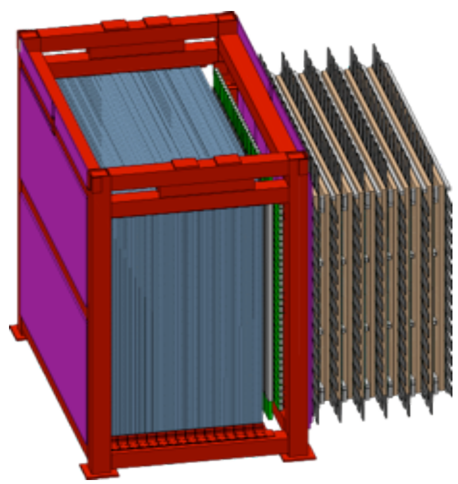
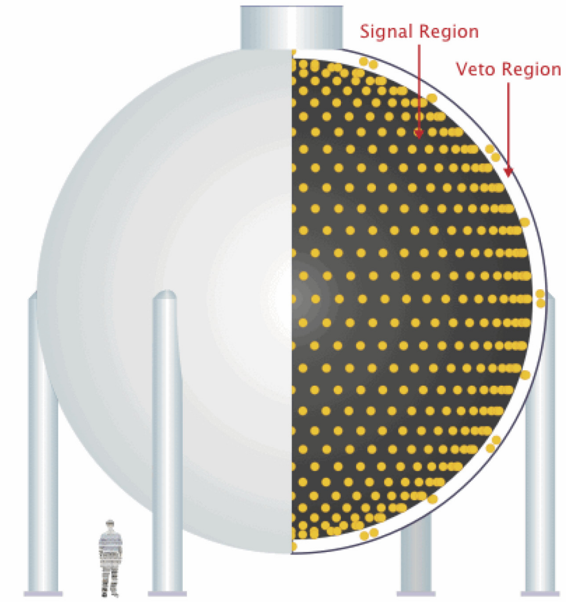
Joint MiniBooNE, SciBooNE $\bar{\nu}_\mu$ Disappearance Analysis

Fermilab
31 Aug 2012





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Acknowledgements

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- Zarko Pavlovic
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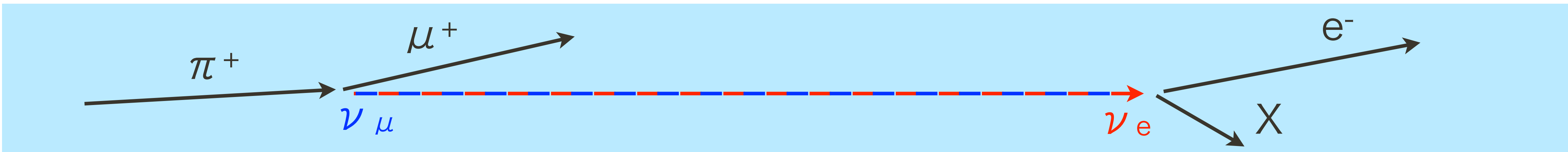
- Muon Neutrino CCQE Cross Section Analysis (Phys. Rev. D81, 092005 (2010))
- Neutrino Contamination in Antineutrino Mode (Phys. Rev. D84, 072005 (2011) and arXiv: 1107.5327)
- Electron Neutrino (Antineutrino) Appearance (Phys. Rev. Lett. 105 181801 (2010) and arXiv: 1207.4809)
- MiniBooNE/SciBooNE Muon Neutrino Disappearance (Phys. Rev. D85, 032007 (2012))

Outline

- Background and Motivation
  - Neutrino Oscillations and Anomalies
  - Beamline and Detectors
- Analysis Methodology
- Systematic Uncertainties
- Results

Neutrino Oscillations

Neutrinos can change their flavors if neutrinos have finite masses and if the weak and mass eigenstates are mixed



Weak eigenstate (α = e, μ, τ)

$$|\nu_\alpha\rangle = \sum_i U_{\alpha i} |\nu_i\rangle$$

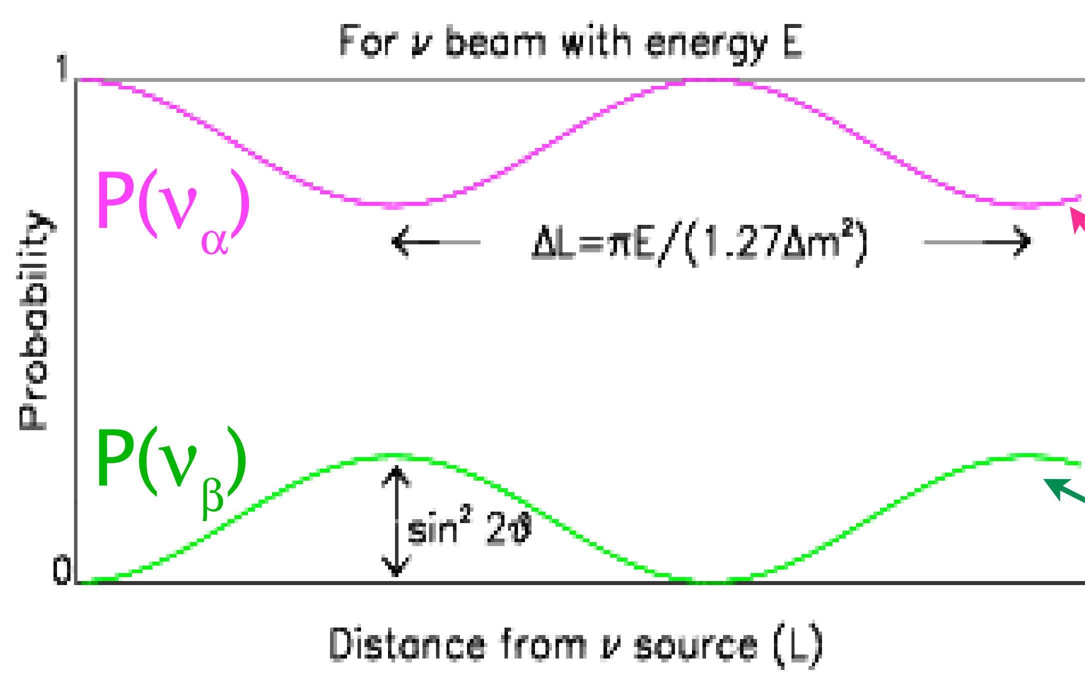
Mass eigenstate (i = 1, 2, 3)

MNS mixing matrix

$$\Delta m_{ij}^2 = m_i^2 - m_j^2$$

Two neutrino case:

$$\boxed{P(\nu_\alpha \to \nu_\beta) \;=\; |\langle\nu_\beta|\nu(t)\rangle|^2 = \sin^2 2\theta \sin^2\left(\frac{1.27\Delta m^2[\mathrm{eV}^2]L[\mathrm{km}]}{E[\mathrm{GeV}]}\right)}$$



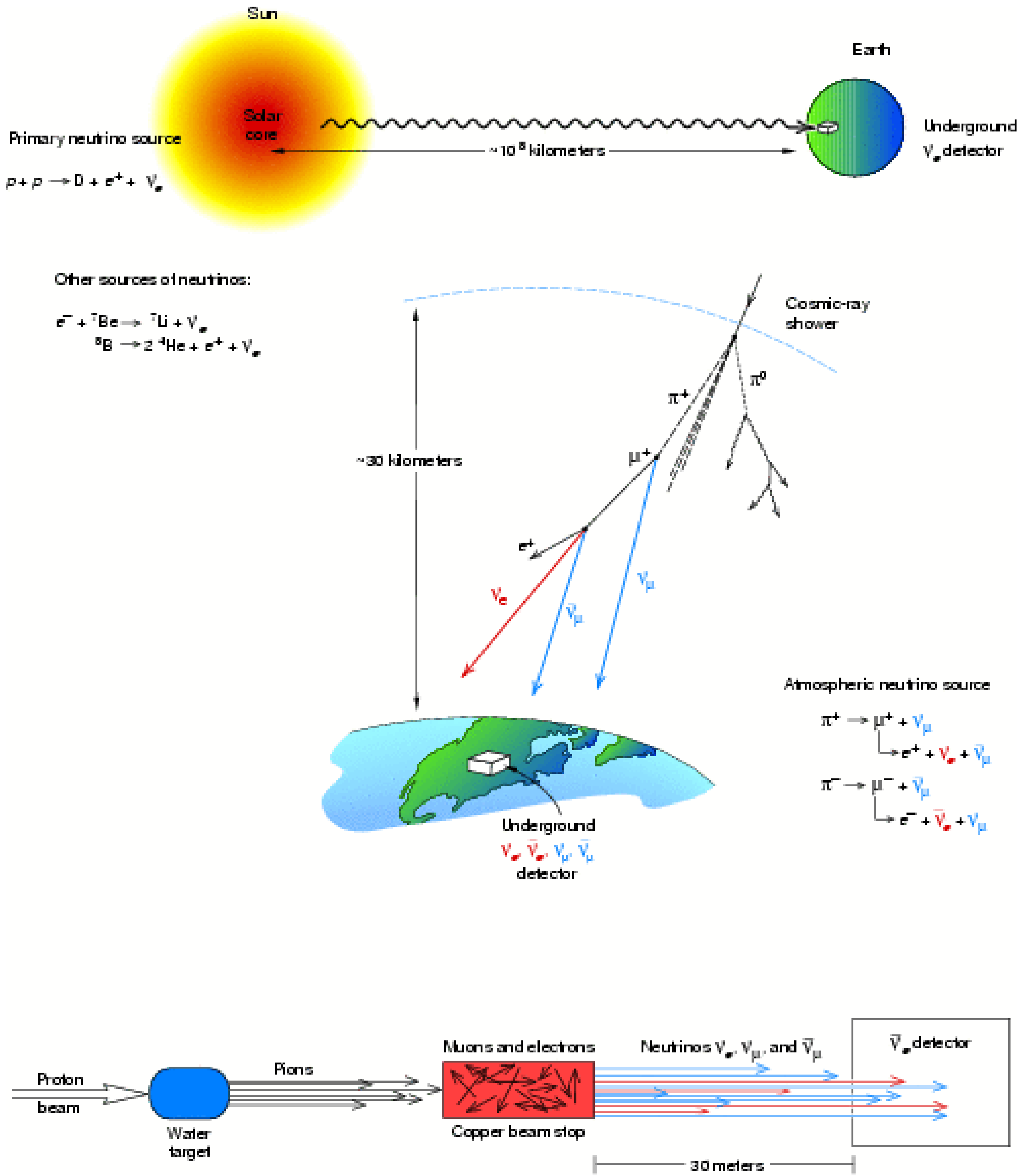
θ	: mixing angle
Δm^2	: mass squared difference
L [km]	: the distance traveled
E (GeV)	: the energy of neutrino

disappearance of ν_α

$$P(\nu_\alpha \to \nu_\alpha) = 1 - P(\nu_\alpha \to \nu_\beta)$$

appearance of ν_β

Neutrino Oscillations Have Been Observed!



SuperK, SNO, KamLAND (Very long baseline)

$\Delta m^2 \sim 10^{-5}\ eV^2$

SuperK, K2K, MINOS (intermediate baseline)

$\Delta m^2 \sim 10^{-3}\ eV^2$

$$\Delta m_{ij}^2 = m_i^2 - m_j^2$$

LSND? (short baseline)

$\Delta m^2 \sim 1\ eV^2$

Short Baseline (L/E~1) Anomalies

Gallium Anomaly: ν_e Disappearance?

- SAGE and GALLEX gallium solar neutrino experiments used MCi ^{51}Cr and ^{37}Ar sources to calibrate their detectors
  - A recent analysis claims a significant (3σ) deficit
    (Giunti and Laveder, 1006.3244v3 [hep-ph])
    - Ratio (observation/prediction) = 0.76 ± 0.09
    - An oscillation interpretations gives $\sin^2 2\theta > 0.07, \Delta m^2 > 0.35 eV^2$

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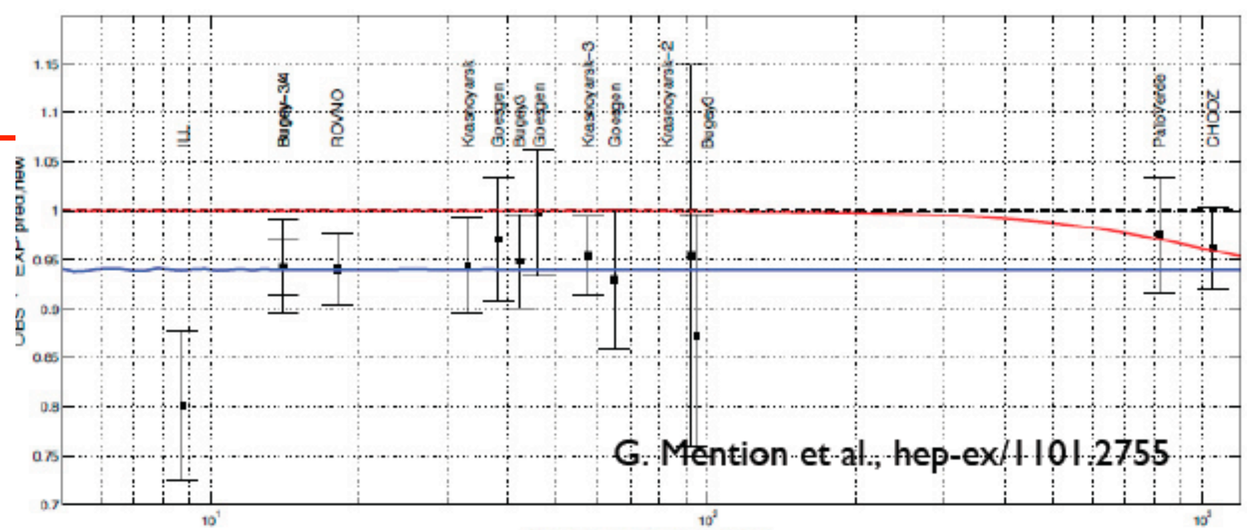
Reactor Antineutrino Anomaly

Re-analysis of predicted reactor fluxes based on a new approach for the conversion of the measured electron spectra to anti-neutrino spectra.

- Reactor flux prediction increases by 3%.
- Re-analysis of reactor experiments show a deficit of electron anti-neutrinos compared to this prediction – at the 2.14σ level
- Could be oscillations to sterile with $\Delta m^2 \sim 1 eV^2$ and $\sin^2 2\theta \sim 0.1$

Red: Oscillations assuming 3 neutrino mixing
Blue: Using a 3+1 (sterile neutrino) model



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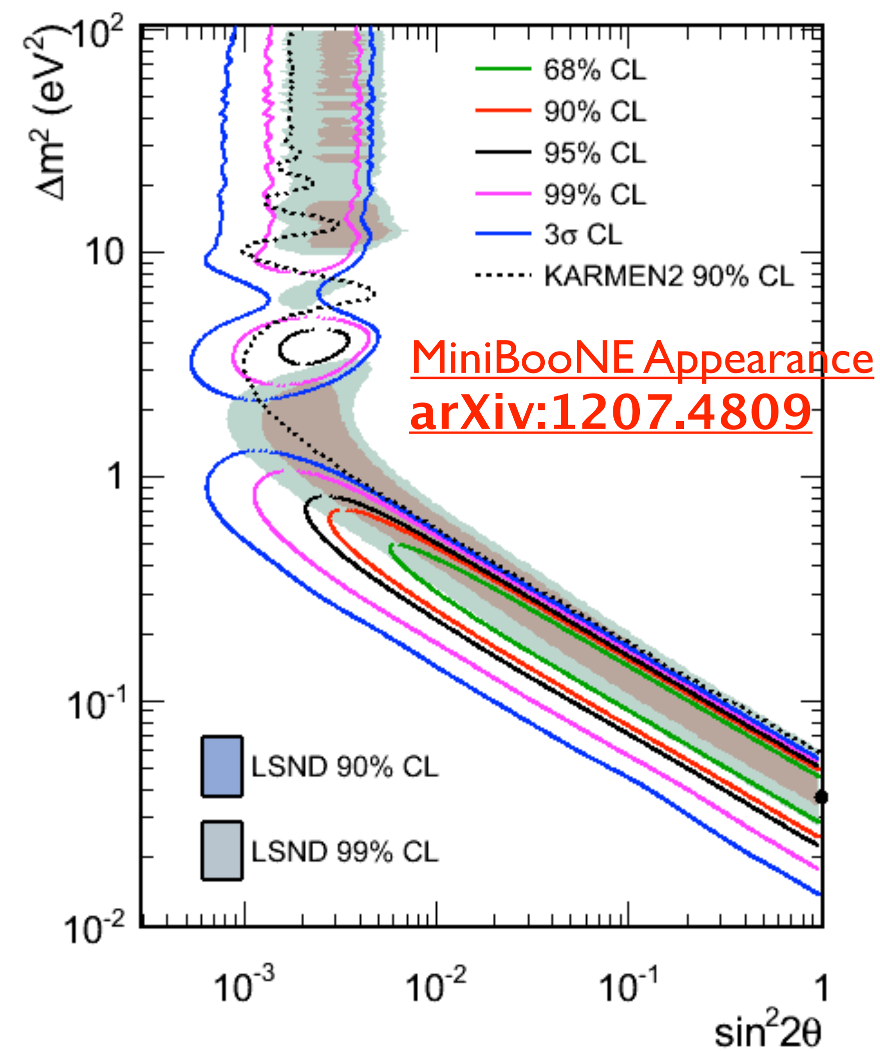

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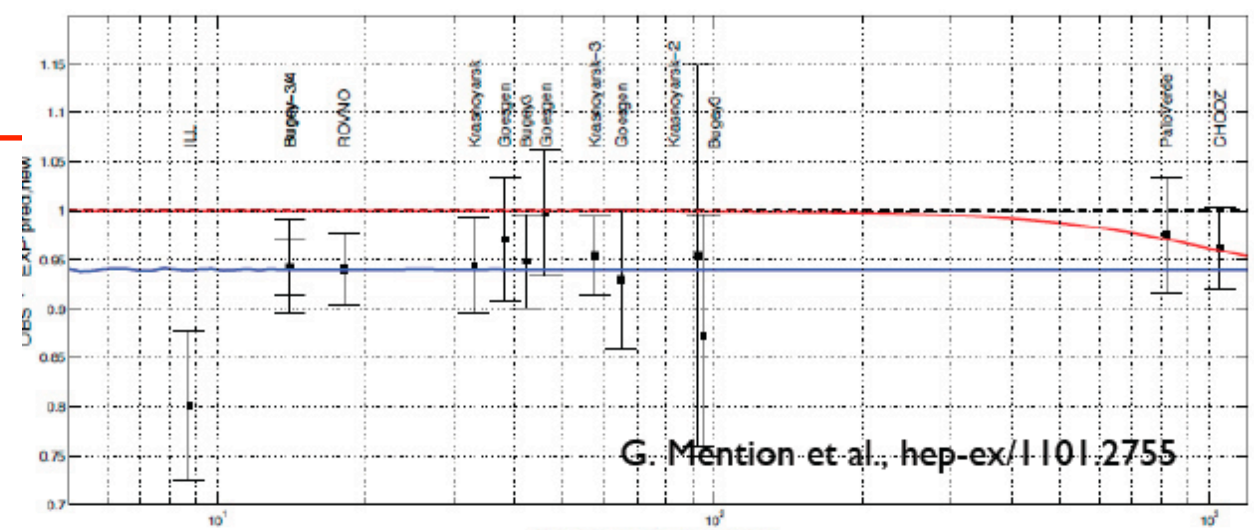
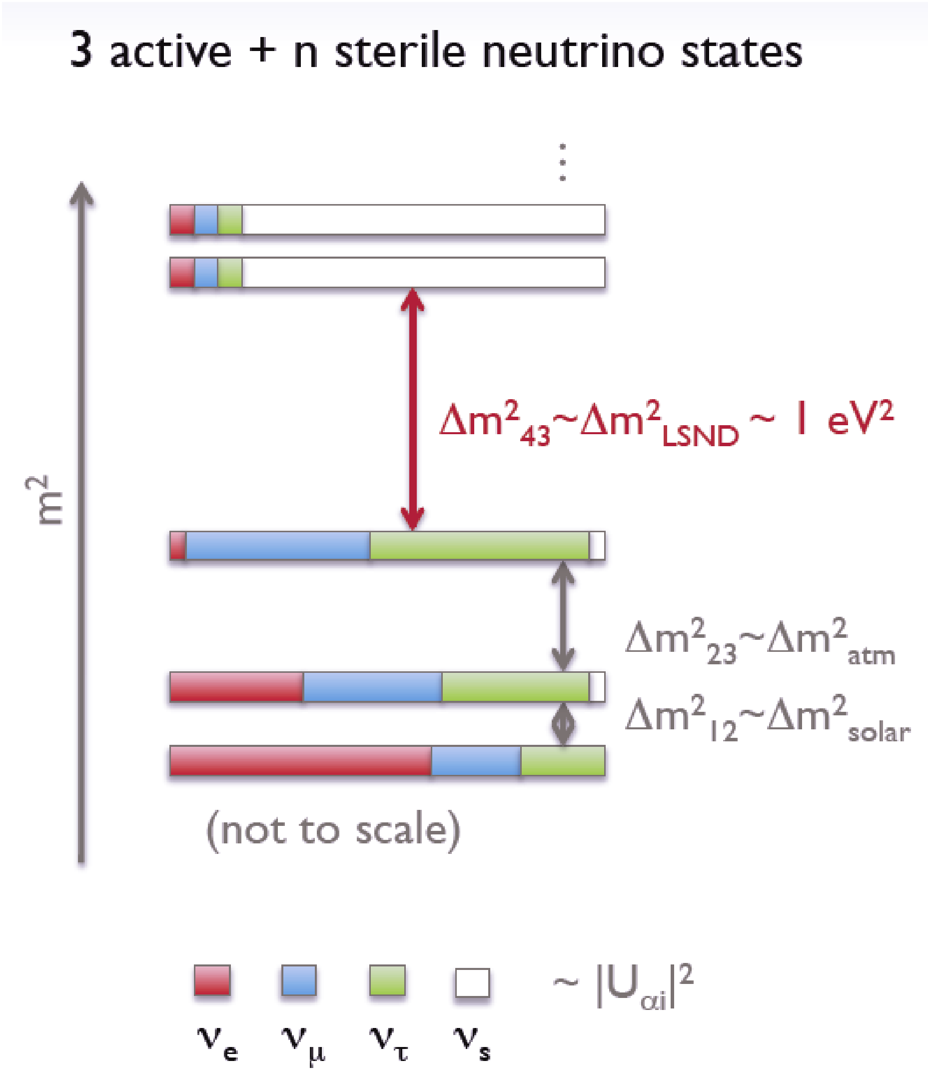


Sterile Neutrinos and Oscillations



$\nu_\mu \rightarrow \nu_e$ appearance

$$P(\nu_\mu \rightarrow \nu_e) = \boxed{4|U_{e4}|^2}\boxed{|U_{\mu 4}|^2}\sin^2\left[1.27\Delta m^2_{41}\frac{L}{E}\right]$$

ν_e disappearance

$$P(\nu_e \rightarrow \nu_x) = 1 - 4\boxed{|U_{e4}|^2(1-|U_{e4}|^2)}\sin^2\left[1.27\Delta m^2_{41}\frac{L}{E}\right]$$

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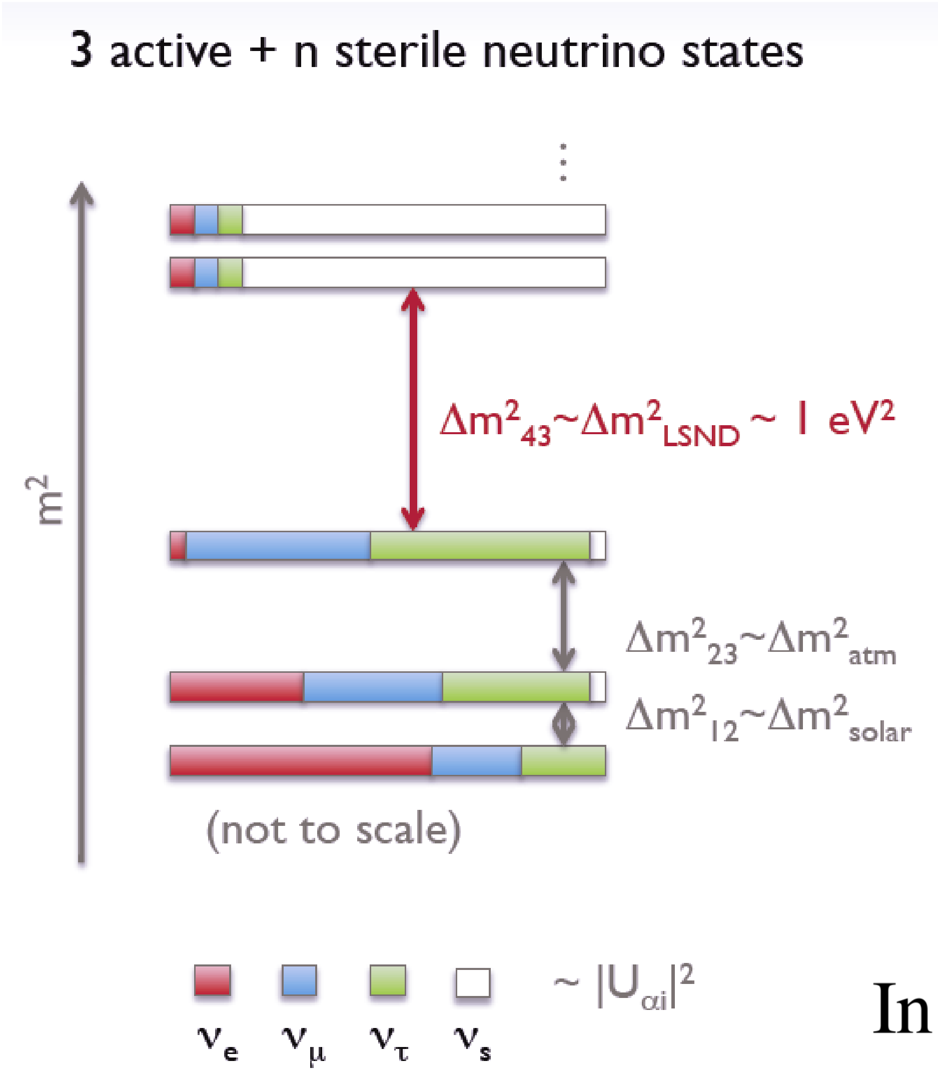

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ν_μ disappearance

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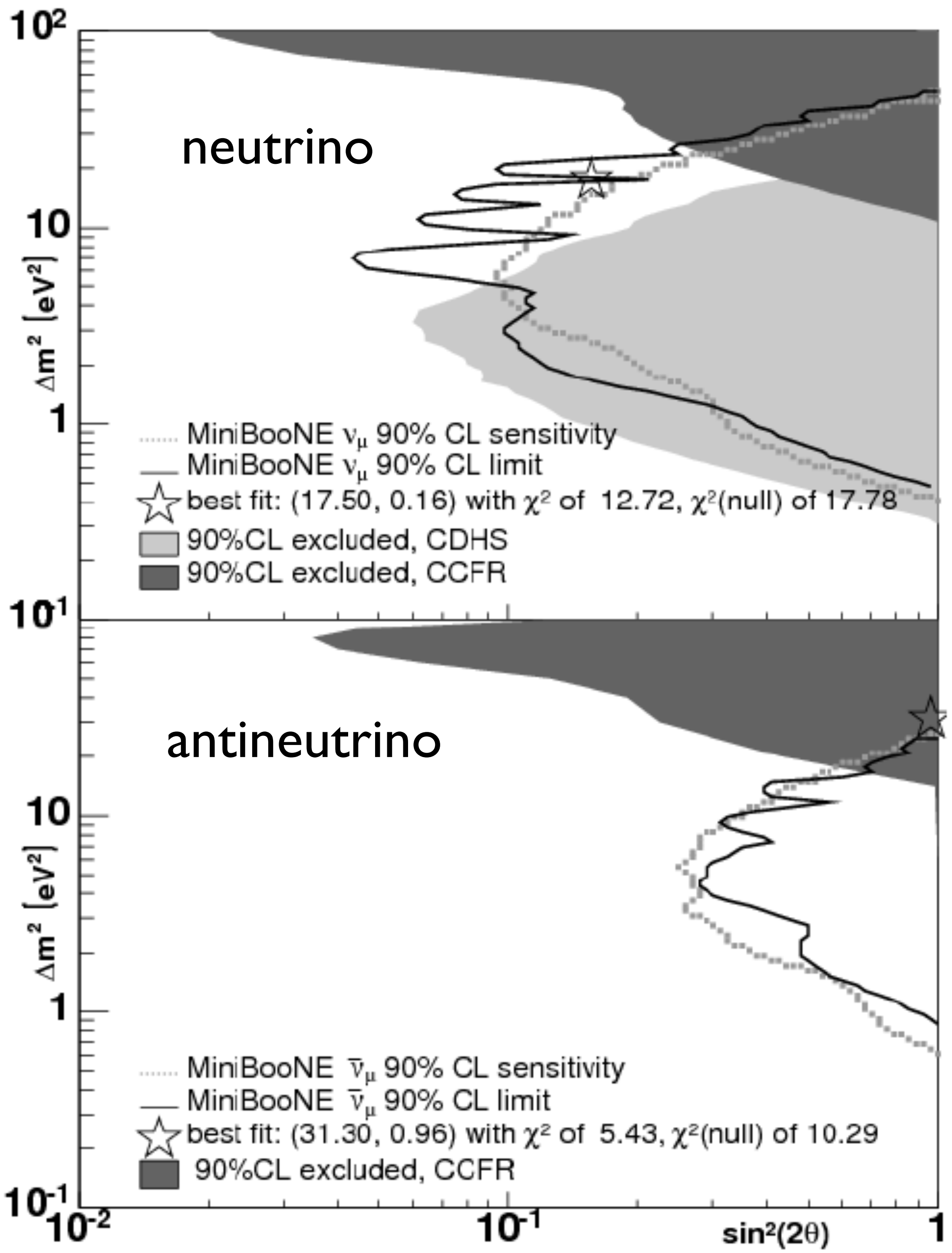
In general: $P(\bar{\nu}_\mu \to \bar{\nu}_e) < \frac{1}{4} P(\bar{\nu}_\mu \to \bar{\nu}_x) P(\bar{\nu}_e \to \bar{\nu}_x)$

LSND and MiniBooNE indicate: $P(\bar{\nu}_\mu \to \bar{\nu}_e) \sim 0.25\%$

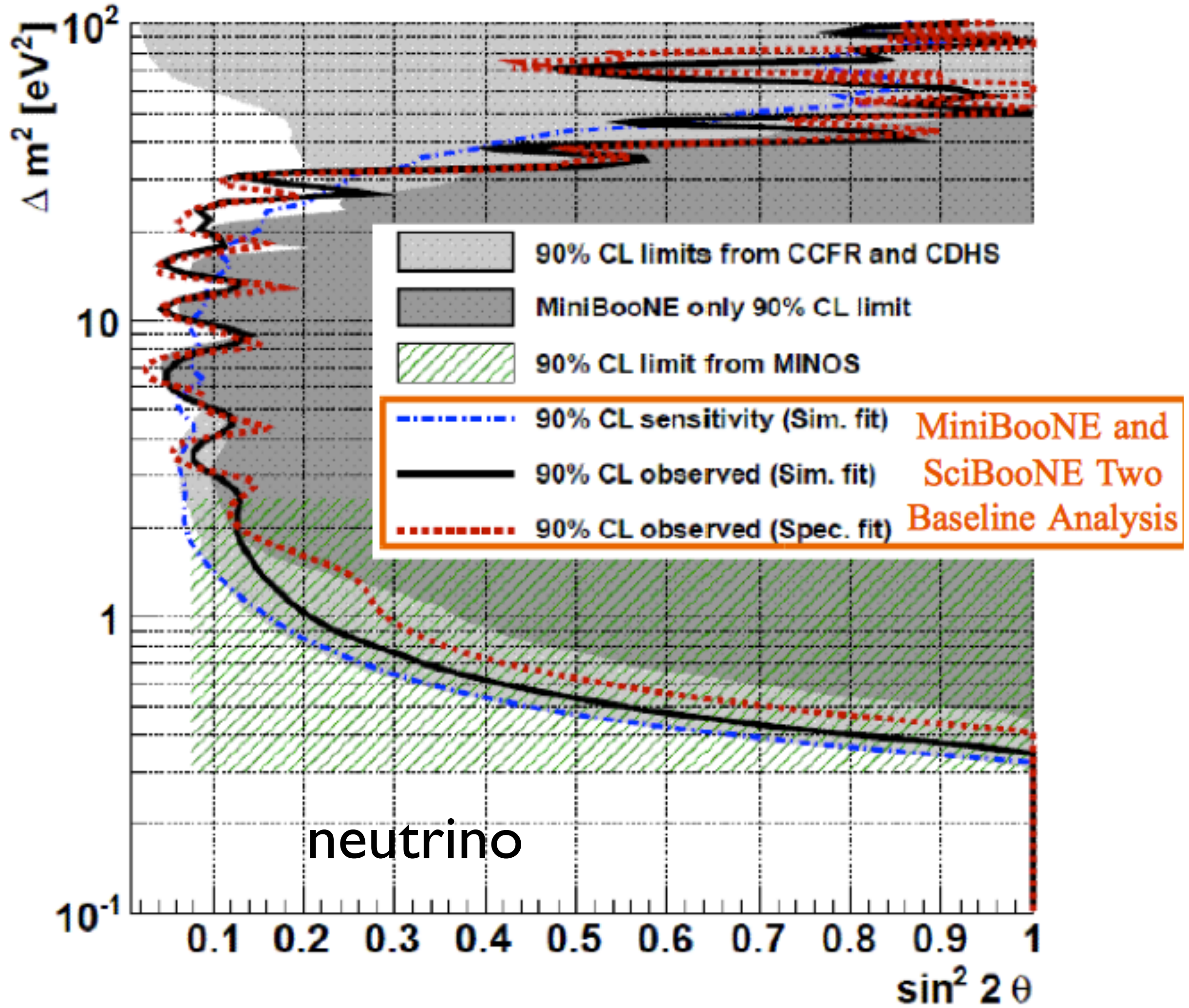
So that if: $P(\bar{\nu}_e \to \bar{\nu}_x) \sim 15\%$

then: $P(\bar{\nu}_\mu \to \bar{\nu}_x) \sim 7\%$

Existing Limits



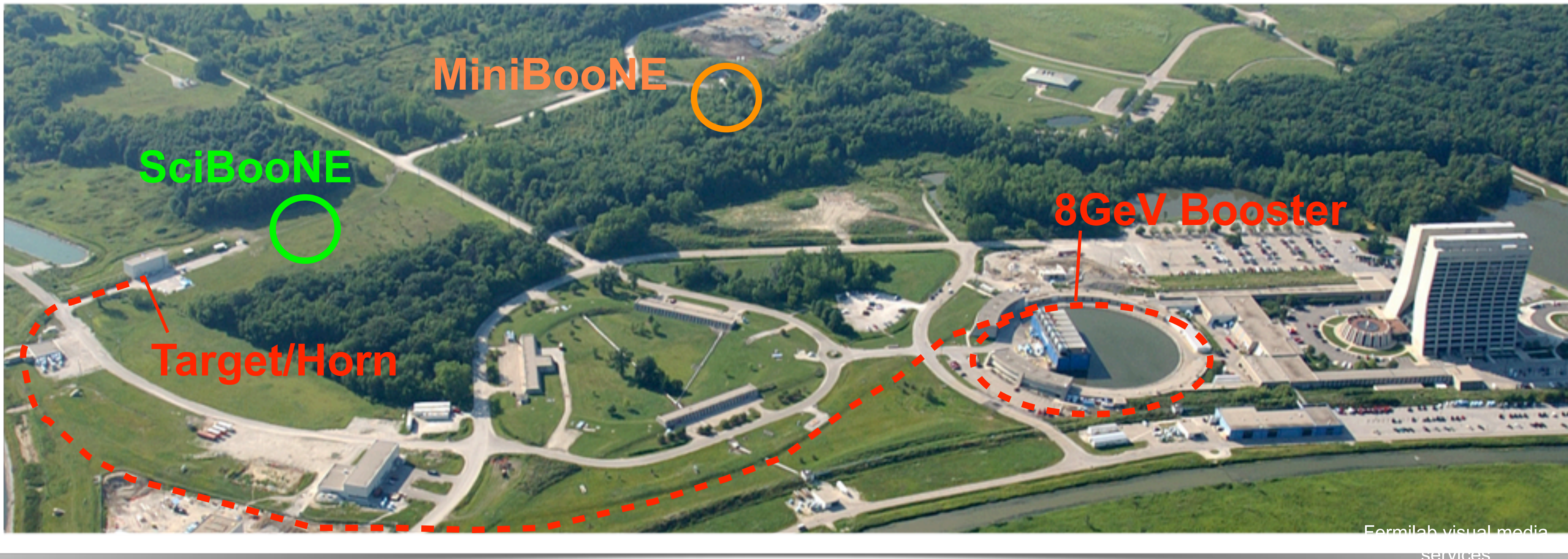
Phys. Rev. Lett 103 061802 (2009)

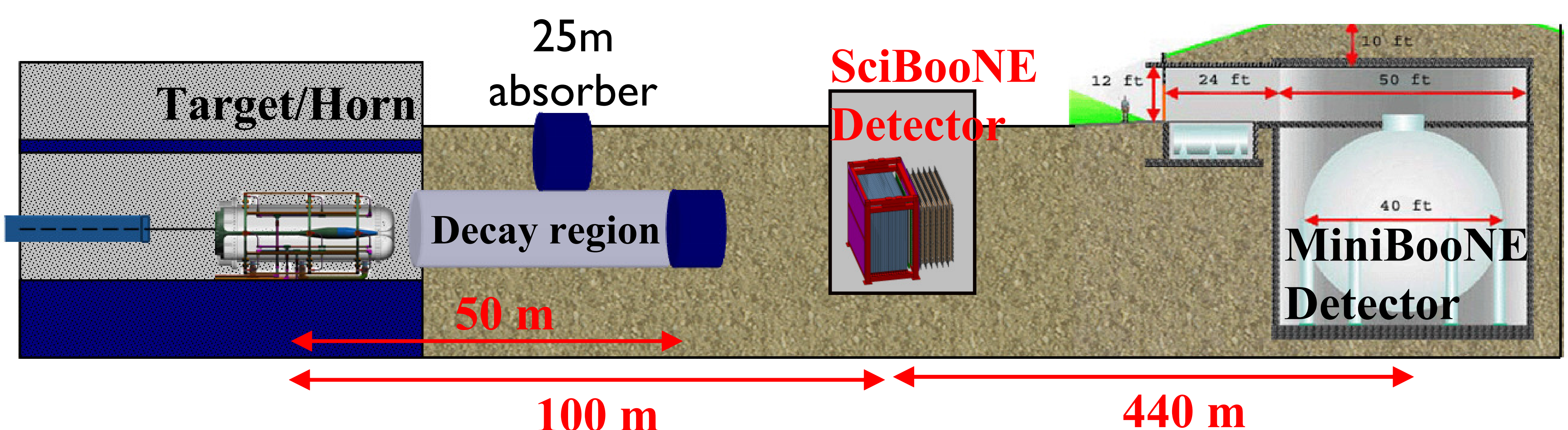


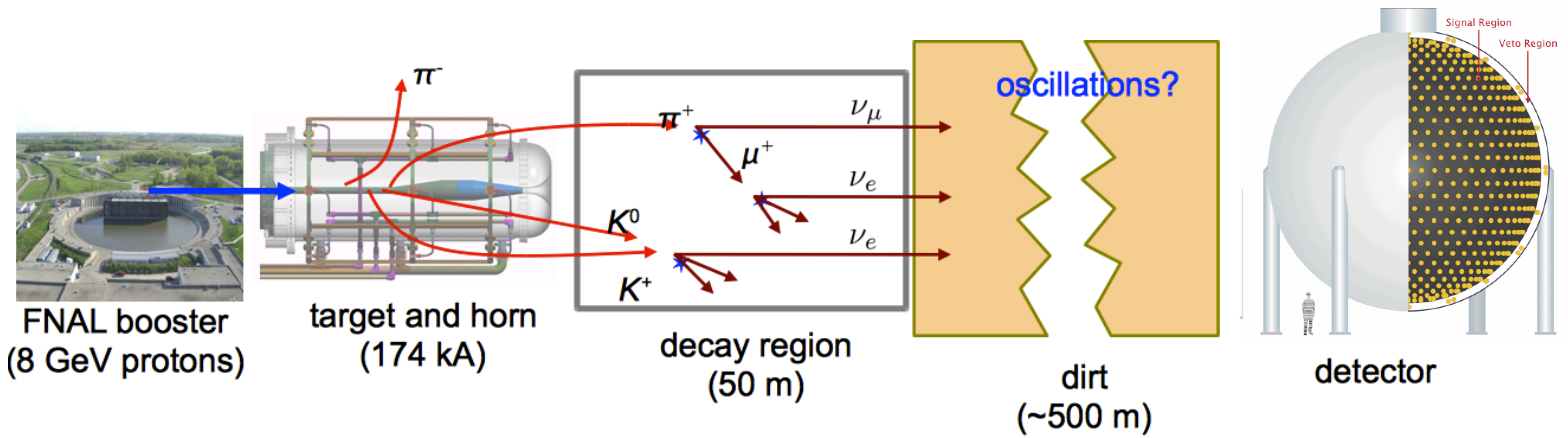
Phys. Rev. D85, 032007 (2012)

(assuming CPT conservation, and no *effective CPT violation*, nu and antinu disappearance should be the same)

Beamline Overview







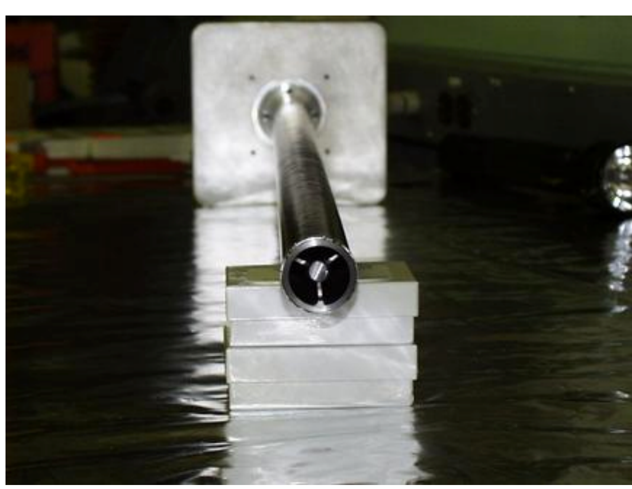
MiniBooNE was designed to test the LSND signal

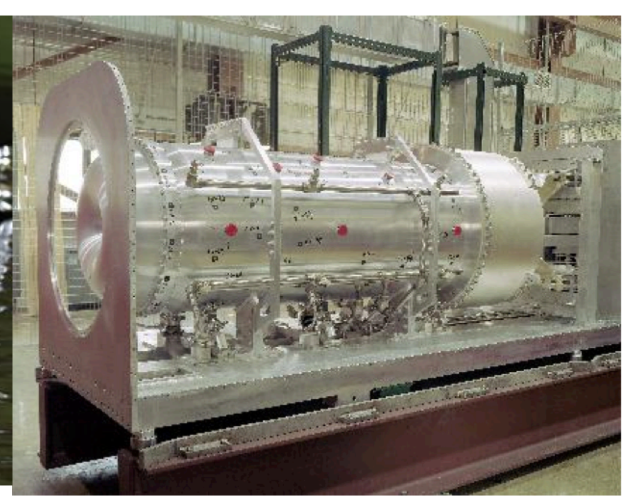
Keep L/E same as LSND
while changing systematics, energy & event signature

- 800t mineral oil Cherenkov detector (520t fiducial)
- 1280 PMTs in inner region
- 240 PMTs in outer, optically isolated veto region

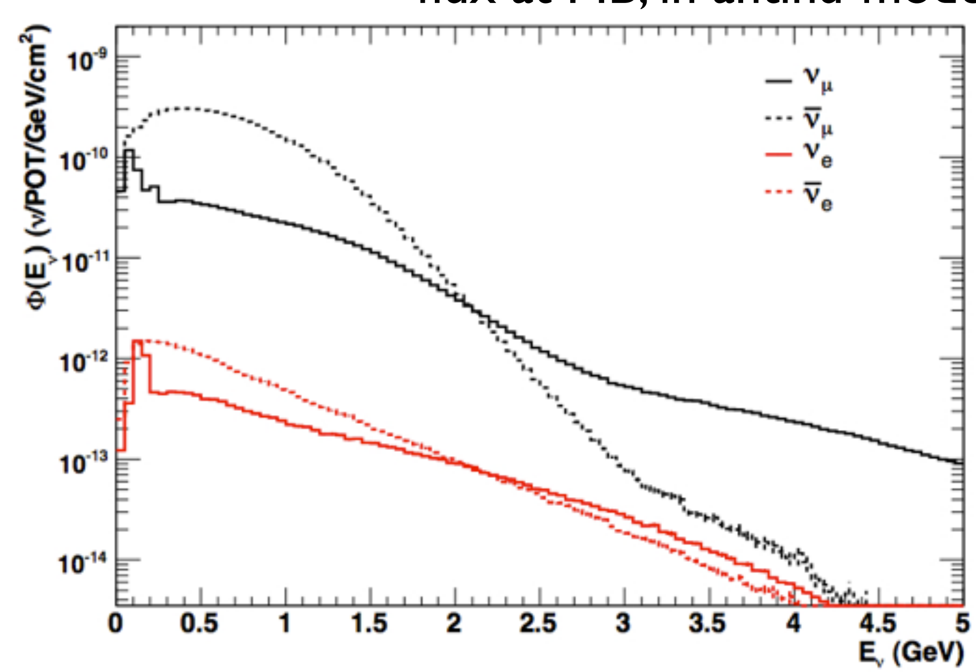
$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta \, \sin^2(1.27 \Delta m^2 L/E)$$ ➔ Two neutrino fits

LSND:	E ~ 30 MeV	L ~ 30 m	L/E ~ 1
MiniBooNE:	E ~ 500 MeV	L ~ 500 m	L/E ~ 1

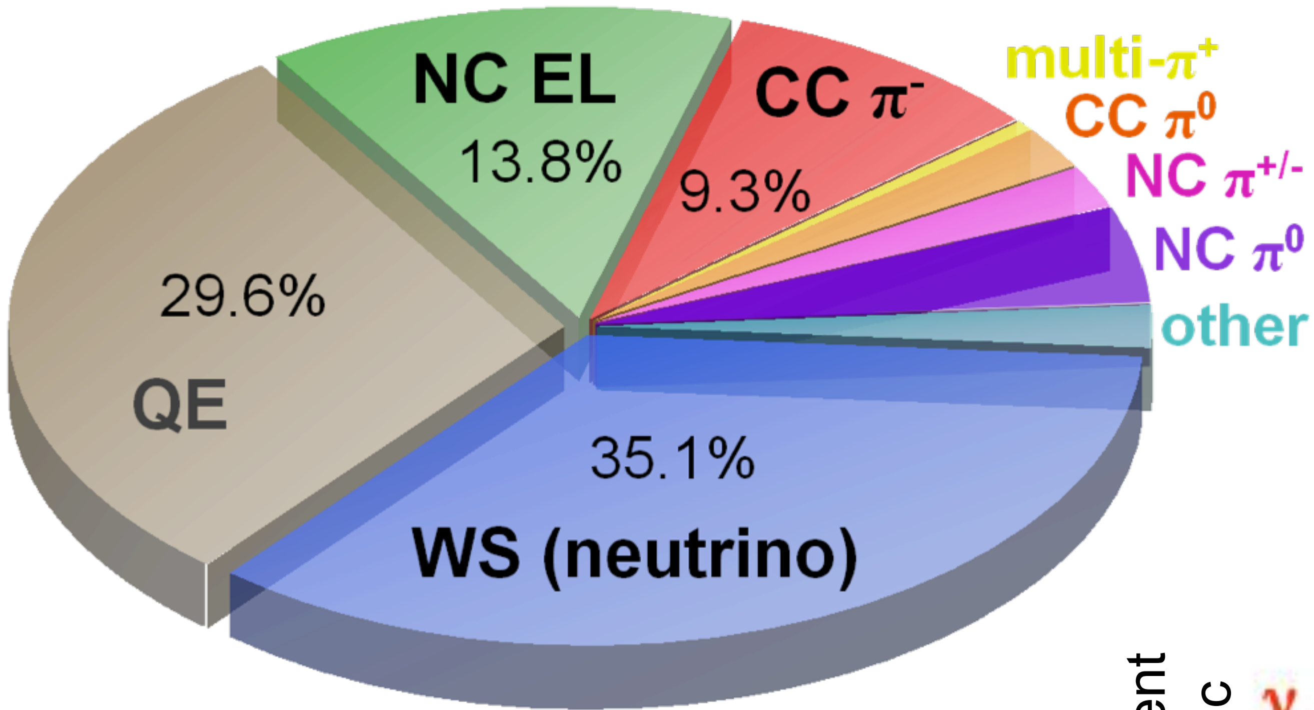




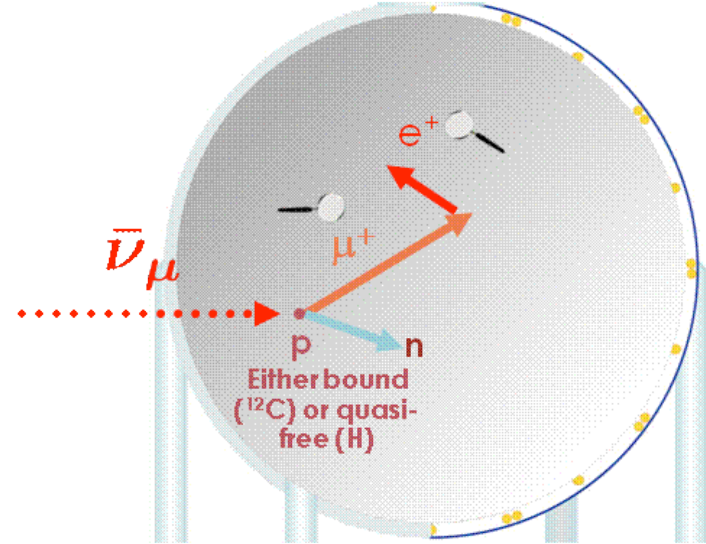
flux at MB, in antinu-mode



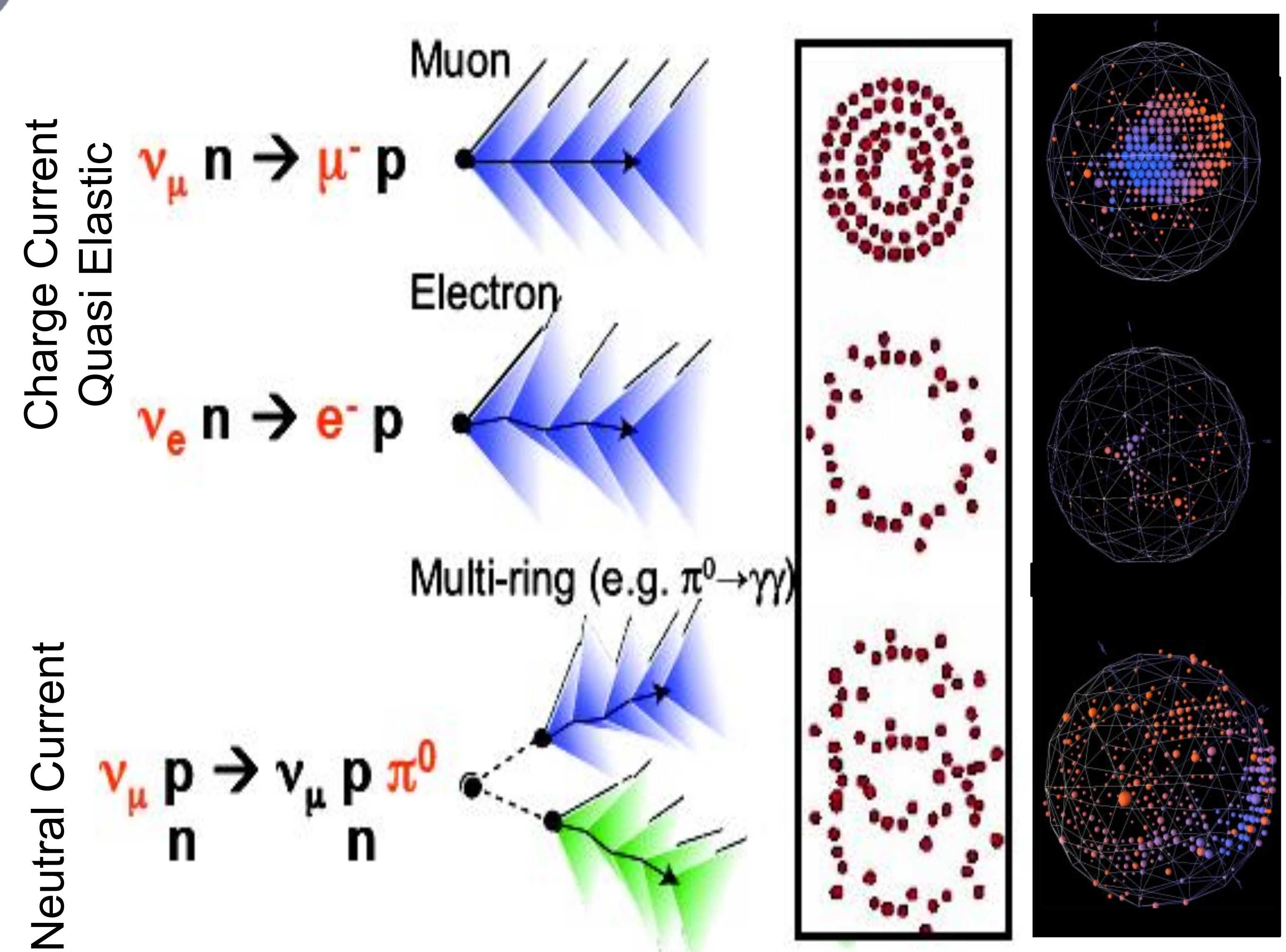
Particle ID in MiniBooNE



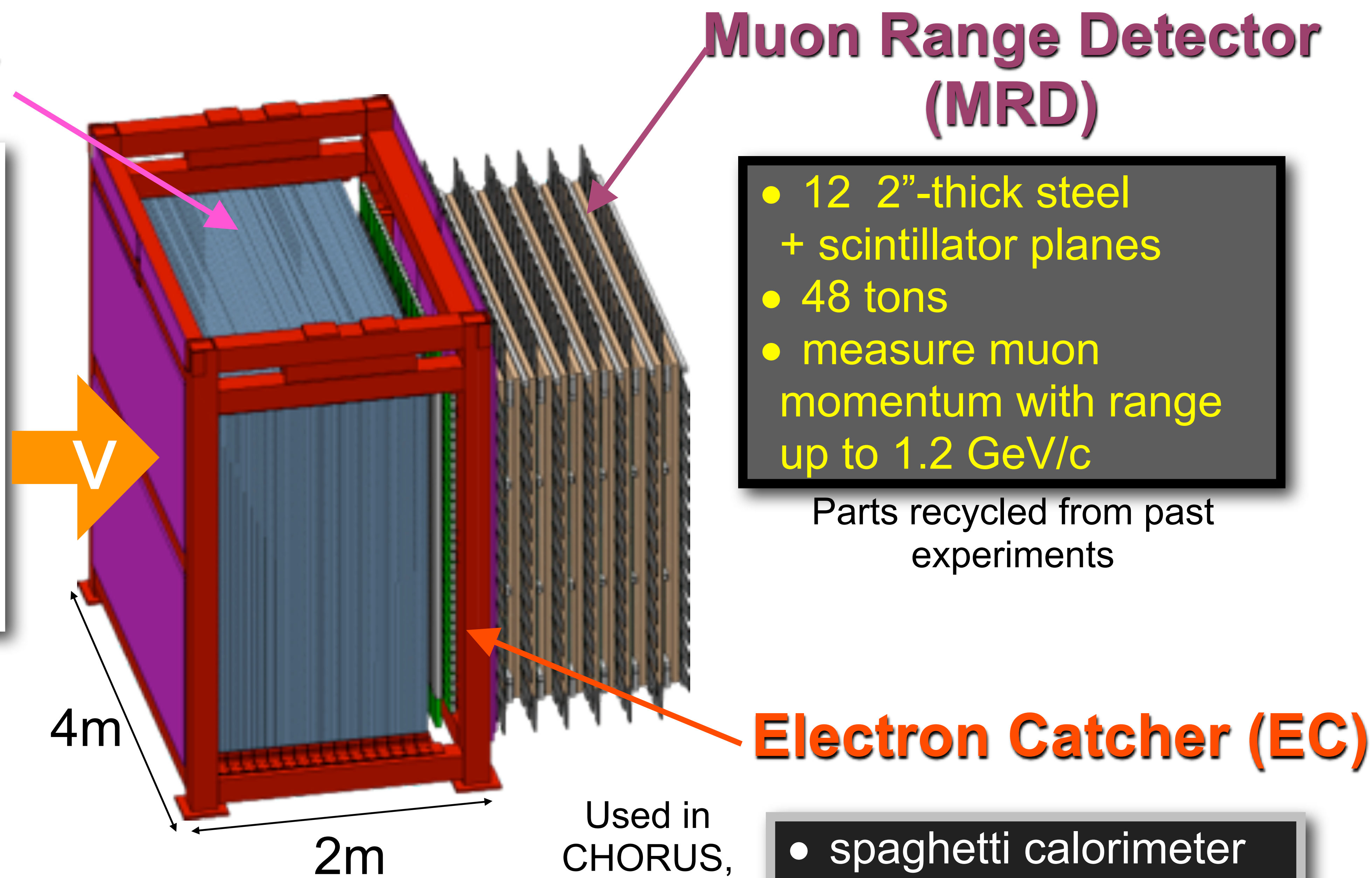
Nuance MC Prediction: Interactions in MiniBooNE
(antineutrino mode)



- Ring imaging for event reconstruction and particle ID
- Particle decays used for event ID: separate clusters of PMT hits in time (subevents)
- Veto region ensures containment, reduces cosmic background to negligible level



SciBooNE Detector



- scintillator tracking detector
- 14,336 scintillator bars (15 tons)
- Neutrino target
- detect all charged particles
- p/π separation using dE/dx

Used in K2K experiment

- 12 2”-thick steel + scintillator planes
- 48 tons
- measure muon momentum with range up to 1.2 GeV/c

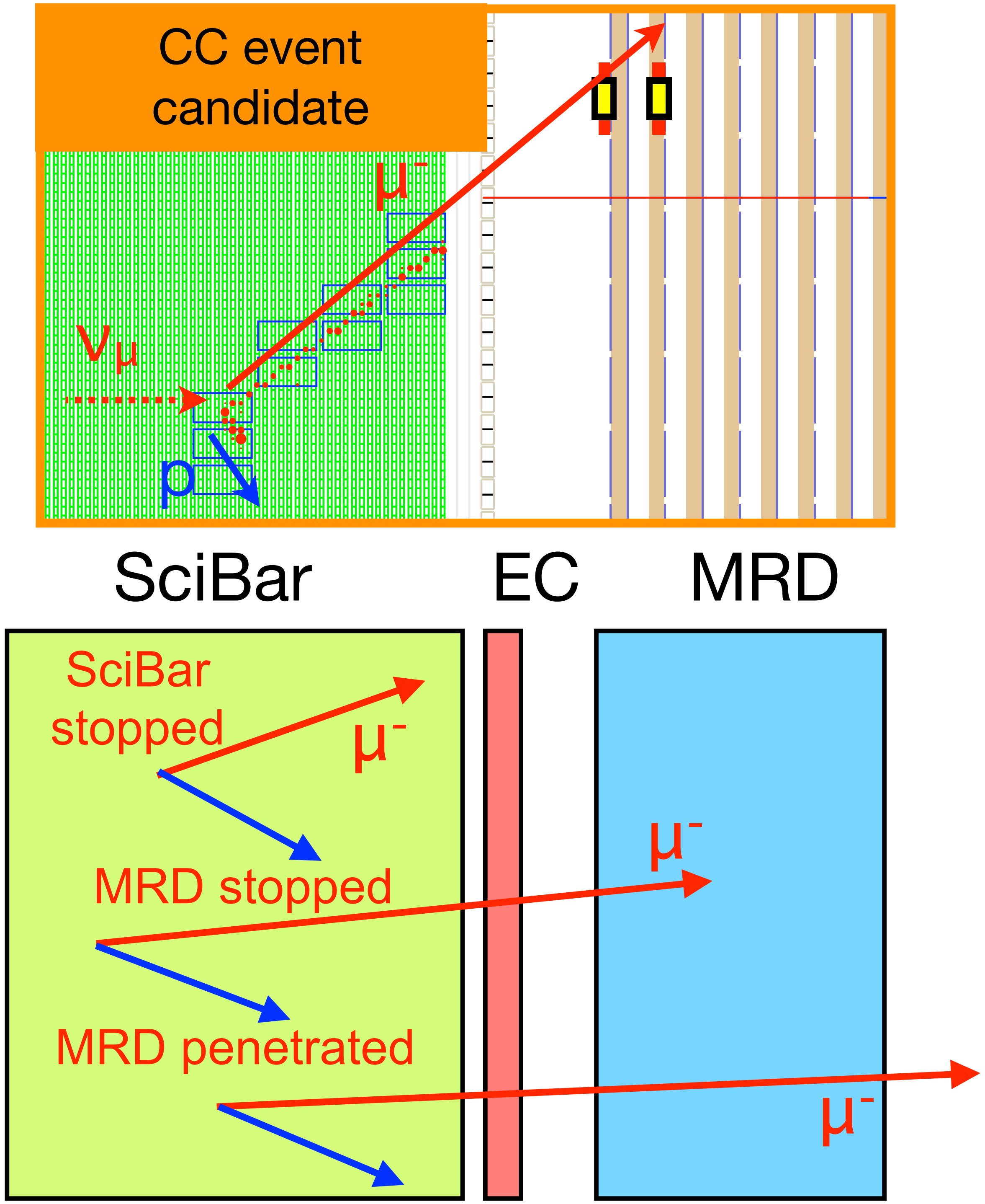
Parts recycled from past experiments

Used in CHORUS, HARP and K2K

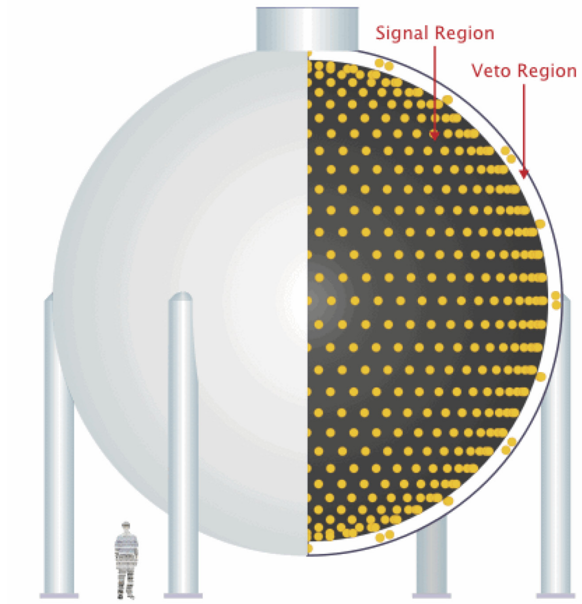
- spaghetti calorimeter
- 2 planes (11 X_0)
- identify π^0 and ν_e

- Precise measurement of neutrino cross sections for future oscillation experiments
- MiniBooNE near detector

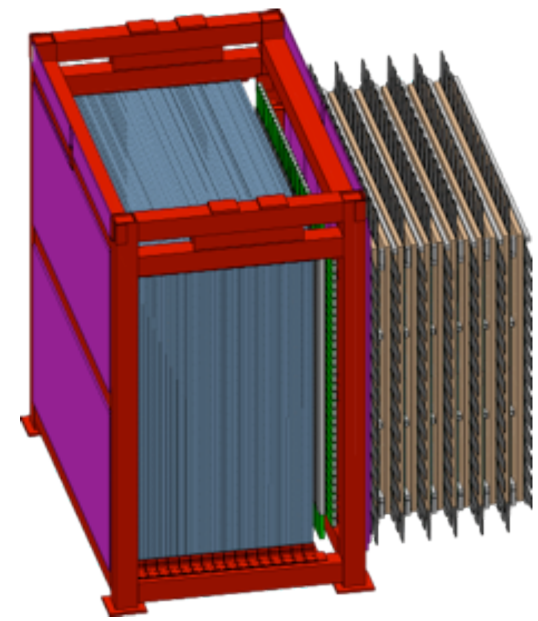
Particle ID in SciBooNE



- Reject escaping muons
- Samples used:
  - SciBar-stopped
  - MRD-stopped
- SciBooNE sample is "CC-inclusive"
- Both detectors (MB and SB) rely on the muon for event reconstruction and energy estimation:
  - P_μ: muon momentum reconstructed by its path-length
  - θ_μ: muon angle w.r.t. beam axis



Data Periods



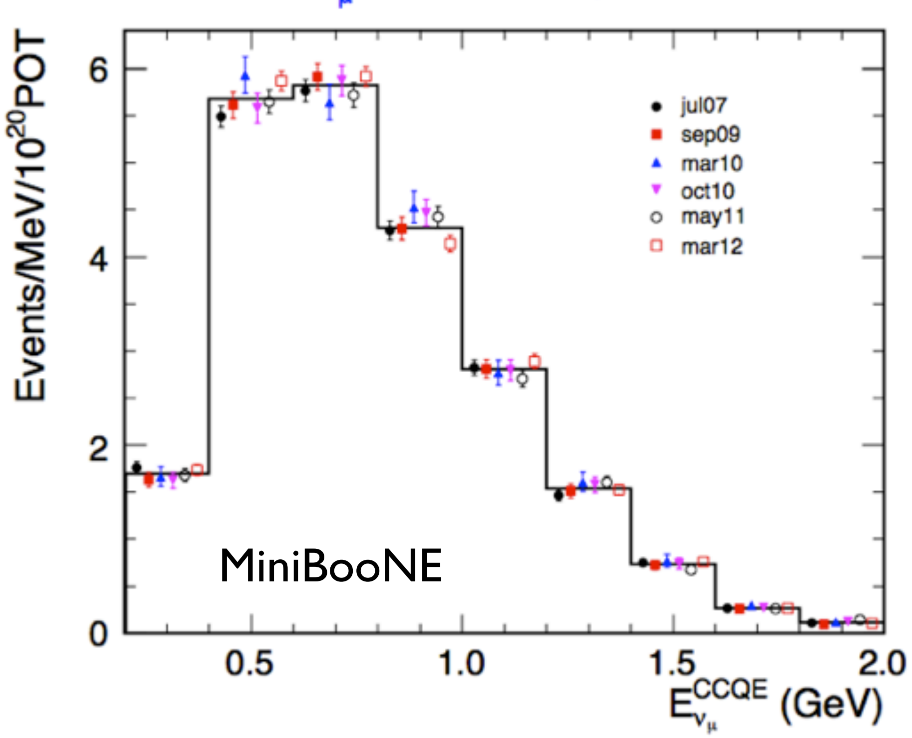
MiniBooNE

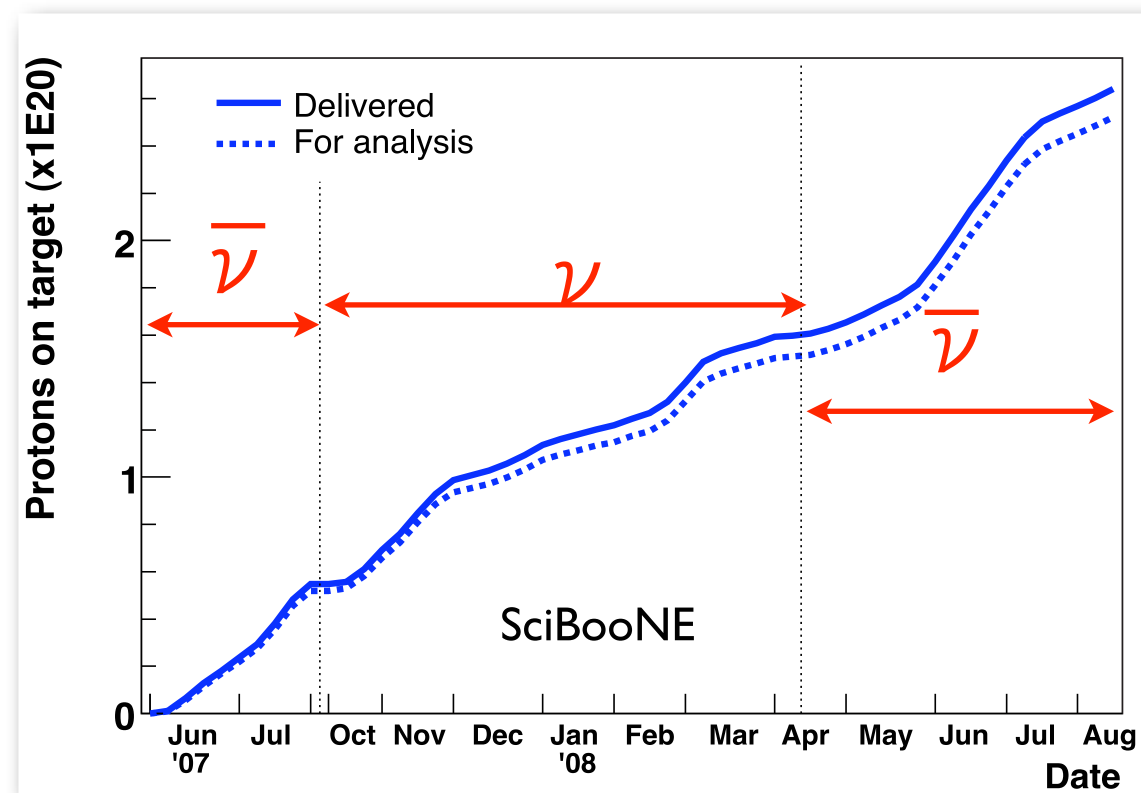
- Data taking: 2002-2012
- Total POT: 19.8×10^{20}
- Neutrino mode: 6.5×10^{20} POT
- Antineutrino mode: 11.3×10^{20} POT (used 10.1×10^{20} POT)

SciBooNE

- Data taking: Jun 2007-Aug 2008
- Total POT: 2.53×10^{20}
- Neutrino mode: 0.99×10^{20} POT
- Antineutrino mode: 1.53×10^{20} POT

$\bar{\nu}_\mu$ CCQE Sample



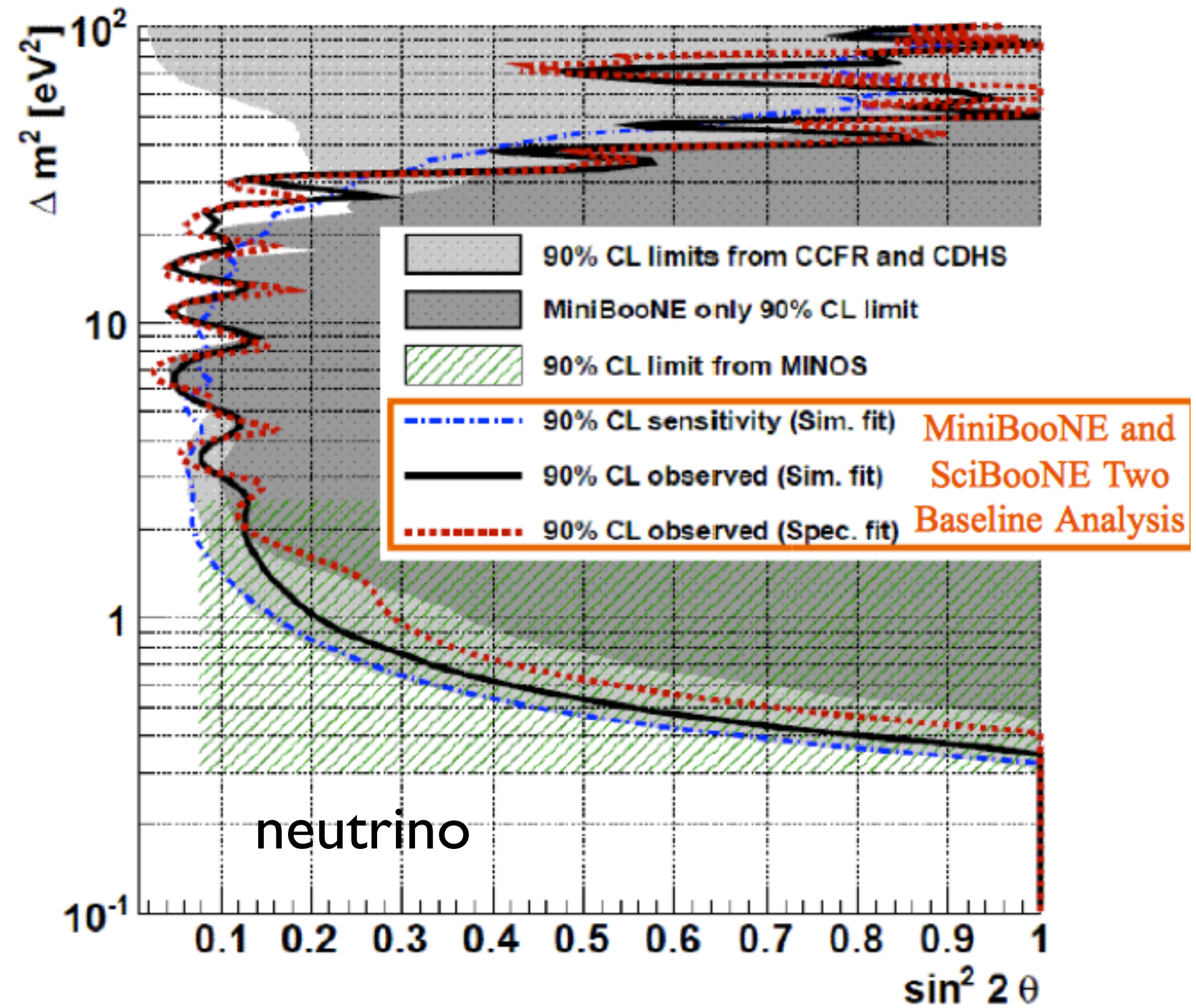


MiniBooNE vs SciBooNE

- different geometries (angular acceptance)
- different material (different C-H ratio)
- different event selection, different event content in final samples
- different methods for rejection of cosmic ray muons
- flux and cross section uncertainties do not fully cancel
- different detector-specific systematics

Antineutrino Mode vs Neutrino Mode

- Have to deal with large neutrino contamination (21% of events in MB, 23% in SB)
- Charged current interactions on hydrogen as well as carbon
- Different constraints for neutrino vs antineutrino events



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Fit Method

- Simultaneous fit to MiniBooNE and SciBooNE Reconstructed Energy Distributions
- Only antineutrino events are oscillated in the fits (includes CCQE, CC1pi, etc.); neutrino events are constrained
- Model is simple, 2-neutrino oscillation model:

$$P_{\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu} = 1 - \sin^2 2\theta \sin^2 1.27 \frac{\Delta m^2 L}{E}$$

Test Statistic: $\Delta\chi^2 = \chi^2\left(X(\Theta_{\text{phys}}), M(\Theta_{\text{phys}})\right) - \chi^2\left(X(\Theta_{\text{BF}}), M(\Theta_{\text{BF}})\right)$

$\Theta : \Delta m^2, \sin^2 2\theta$

$$\chi^2 = \sum_{i,j=1}^{n} \left(D_i - X_i\right)\left(M^{-1}\right)_{ij}\left(D_j - X_j\right)$$

D_i = data; 21-bin reconstructed energy distributions from MiniBooNE and SciBooNE

X_i = Monte Carlo predictions for MiniBooNE and SciBooNE = $X_i^{RS}\left(\Delta m^2, \sin^2 2\theta\right) + X_i^{WS}$

M = covariance matrix for uncertainties in total event rate (RS+WS)

21 bins in E_ν^{QE} from 300 MeV to 1.9 GeV, for SB and MB (n = 42)

RS: antineutrinos
WS: neutrinos

Error Matrices

- Correlations between MB and SB uncertainties (flux and cross section) are computed in same framework
- Fractional error matrices that describe the uncertainties and correlations are collapsed and a new total covariance matrix is computed for each prediction as the parameter space is scanned

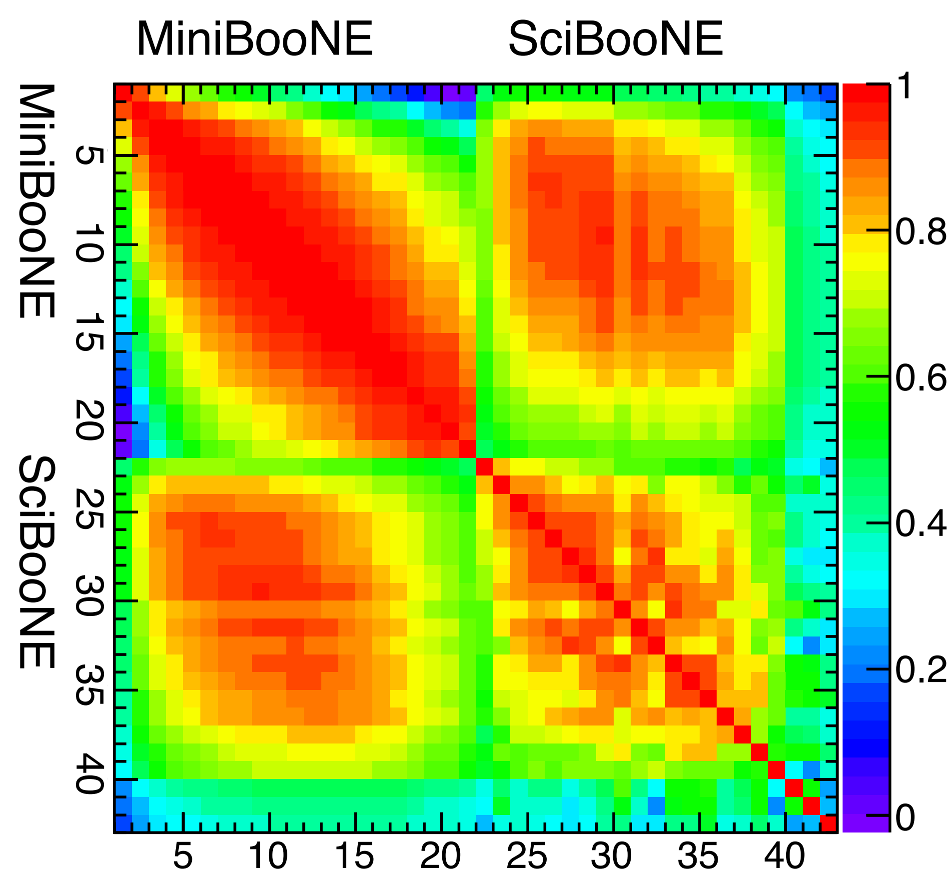
fractional error matrix:

$$\left(\hat{M}_{ij} = \frac{M_{ij}}{x_i x_j}\right)$$

$$\hat{M} = \left(\begin{array}{cc|cc} \hat{M}^{\mathrm{MB}}_{i,j;(RS,RS)} & \hat{M}^{\mathrm{MB}}_{i,j;(RS,WS)} & \hat{M}^{\mathrm{MB,SB}}_{i,j;(RS,RS)} & \hat{M}^{\mathrm{MB,SB}}_{i,j;(RS,WS)} \\ \hat{M}^{\mathrm{MB}}_{i,j;(WS,RS)} & \hat{M}^{\mathrm{MB}}_{i,j;(WS,WS)} & \hat{M}^{\mathrm{MB,SB}}_{i,j;(WS,RS)} & \hat{M}^{\mathrm{MB,SB}}_{i,j;(WS,WS)} \\ \hline \hat{M}^{\mathrm{SB,MB}}_{i,j;(RS,RS)} & \hat{M}^{\mathrm{SB,MB}}_{i,j;(RS,WS)} & \hat{M}^{\mathrm{SB}}_{i,j;(RS,RS)} & \hat{M}^{\mathrm{SB}}_{i,j;(RS,WS)} \\ \hat{M}^{\mathrm{SB,MB}}_{i,j;(WS,RS)} & \hat{M}^{\mathrm{SB,MB}}_{i,j;(WS,WS)} & \hat{M}^{\mathrm{SB}}_{i,j;(WS,RS)} & \hat{M}^{\mathrm{SB}}_{i,j;(WS,WS)} \end{array}\right)$$

$$X = \{X^{MB}_{RS}\left(\Delta m^2, \sin^2 2\theta\right), X^{MB}_{WS}, X^{SB}_{RS}\left(\Delta m^2, \sin^2 2\theta\right), X^{SB}_{WS}\}$$

$$M = X\hat{M}X^T = \begin{pmatrix} M^{\mathrm{MB}} & M^{\mathrm{MB,SB}} \\ M^{\mathrm{SB,MB}} & M^{\mathrm{SB}} \end{pmatrix} + \begin{pmatrix} M^{\mathrm{MB}}_{stat} & 0 \\ 0 & M^{\mathrm{SB}}_{stat} \end{pmatrix}$$



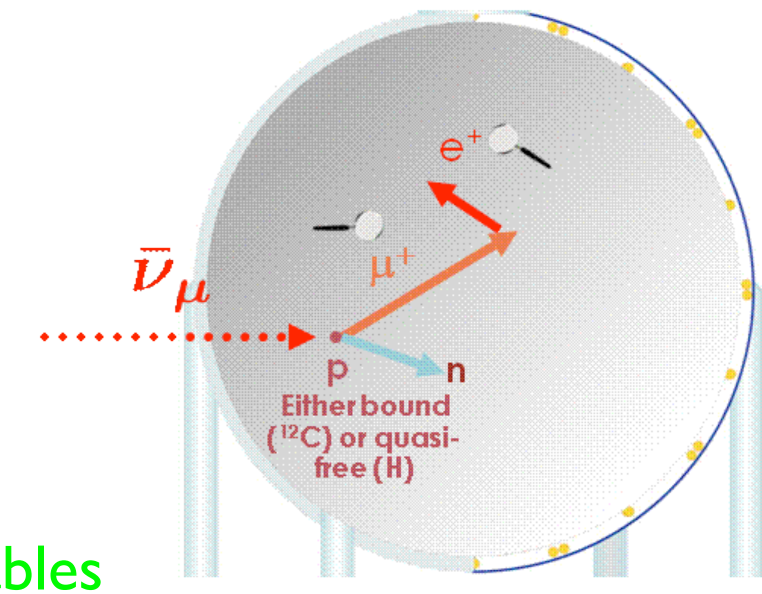
correlation coefficients: $\rho_{ij} = M_{ij} \big/ \left(\sigma_{ii}\sigma_{jj}\right)$

Oscillation of Simulated Events

fit params

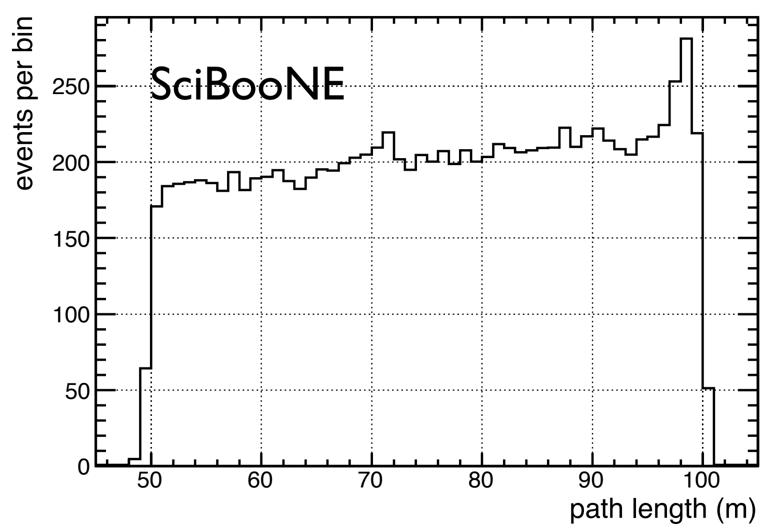
MC truth

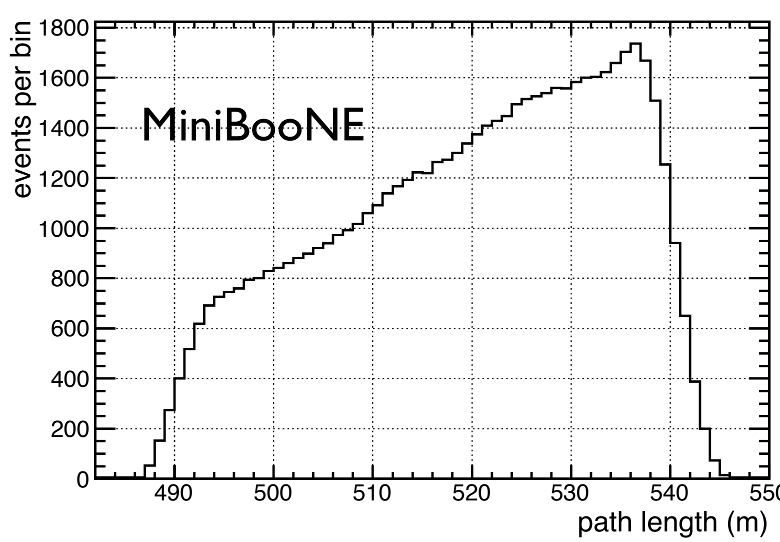
$$P_{\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu} = 1 - \sin^2 2\theta \sin^2 1.27 \frac{\Delta m^2 L}{E}$$



$$E_\nu^{QE} = \frac{M_n^2 - (M_p - E_B)^2 - M_\mu^2 + 2(M_p - E_B)E_\mu}{2(M_p - E_B - E_\mu + P_\mu \cos\theta_\mu)}$$

observables



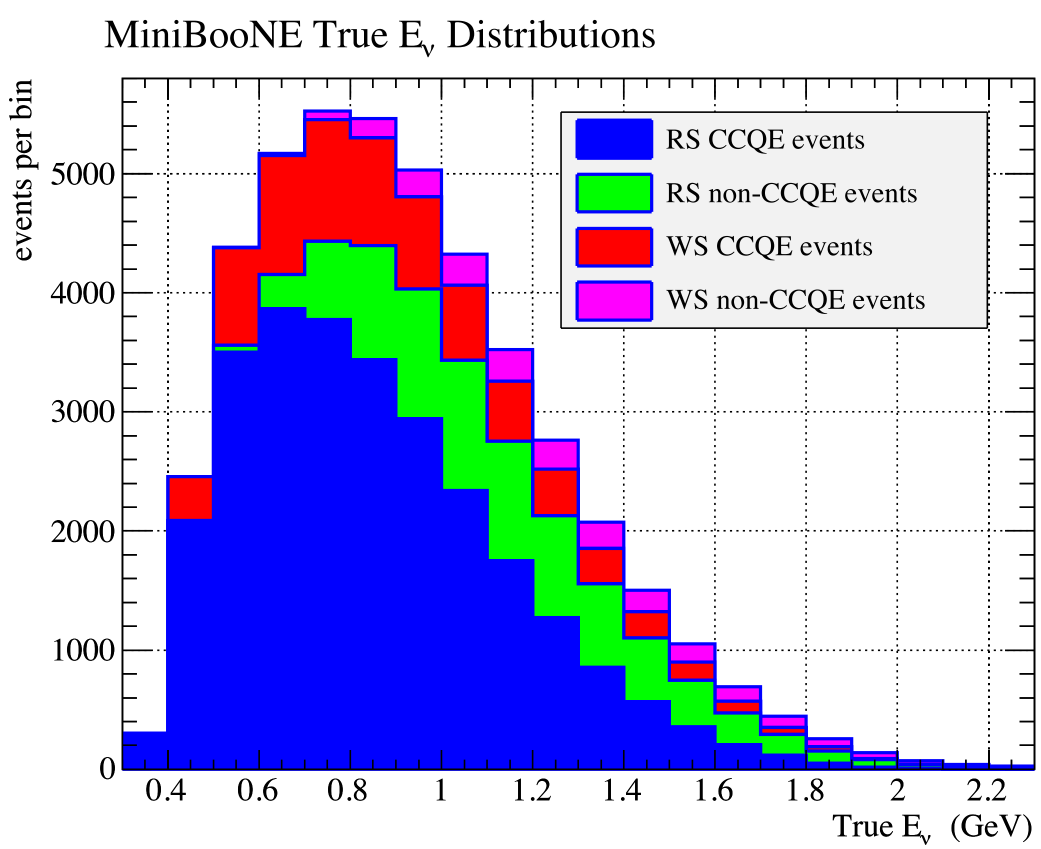


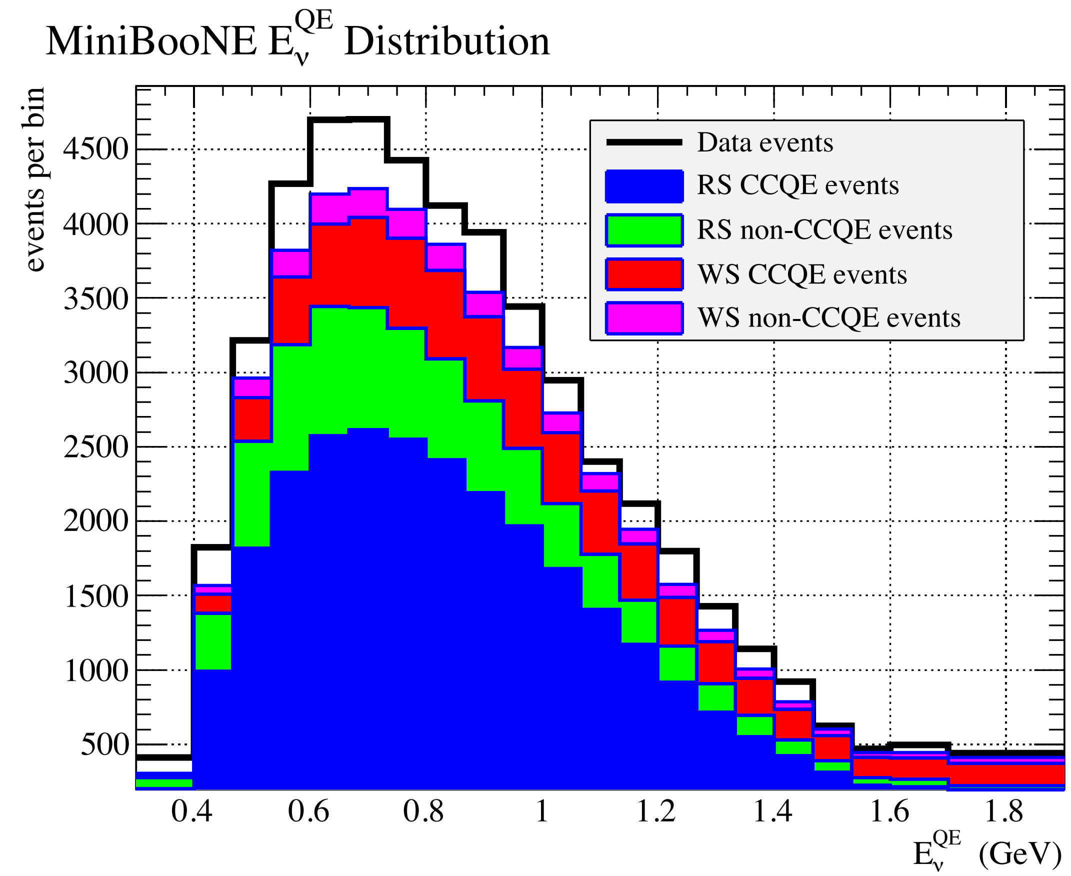
Estimated energy for all events (data and MC) is computed assuming kinematics for muon antineutrino CCQE interaction on Carbon

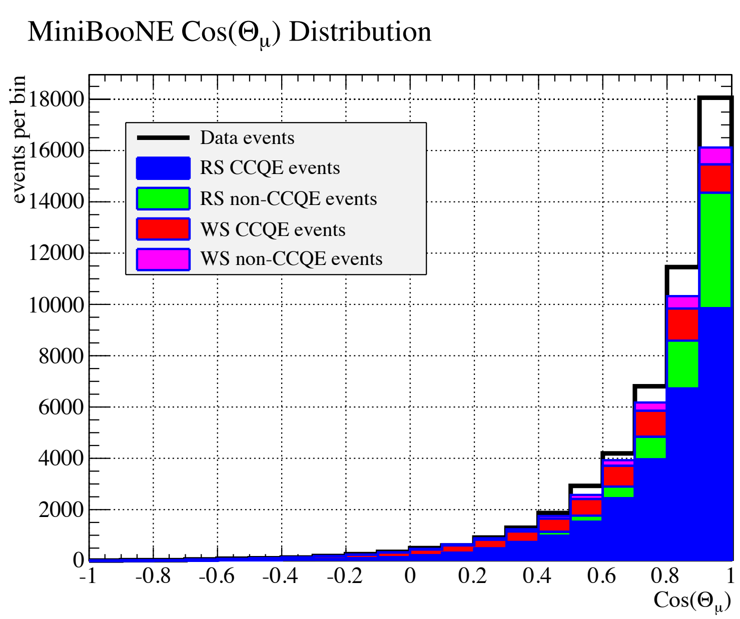
TABLE I. MC predictions for the number of selected events by neutrino and interaction type in both MiniBooNE and SciBooNE.

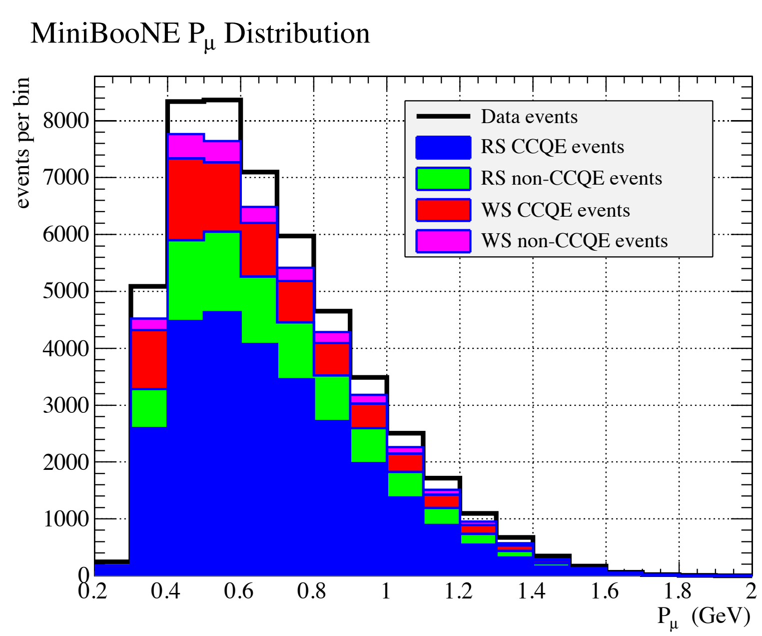
	MiniBooNE		SciBooNE	
interaction type	$\bar{\nu}$ events	ν events	$\bar{\nu}$ events	ν events
CCQE	37428	9955	4619	1359
CC1π	8961	2593	1735	1006
CC multi-π or NC	2364	460	959	610

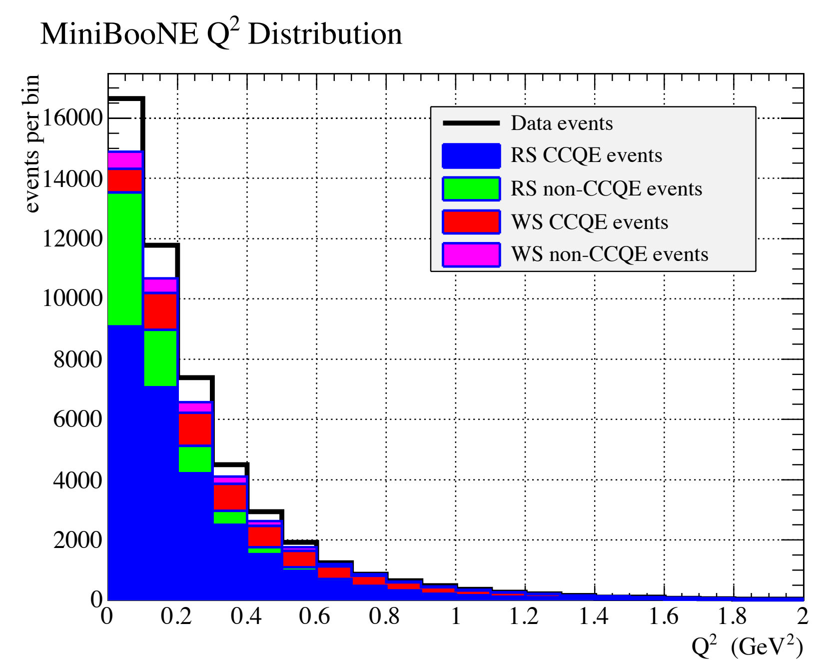
Smearing of Estimated Energy for non-CCQE events







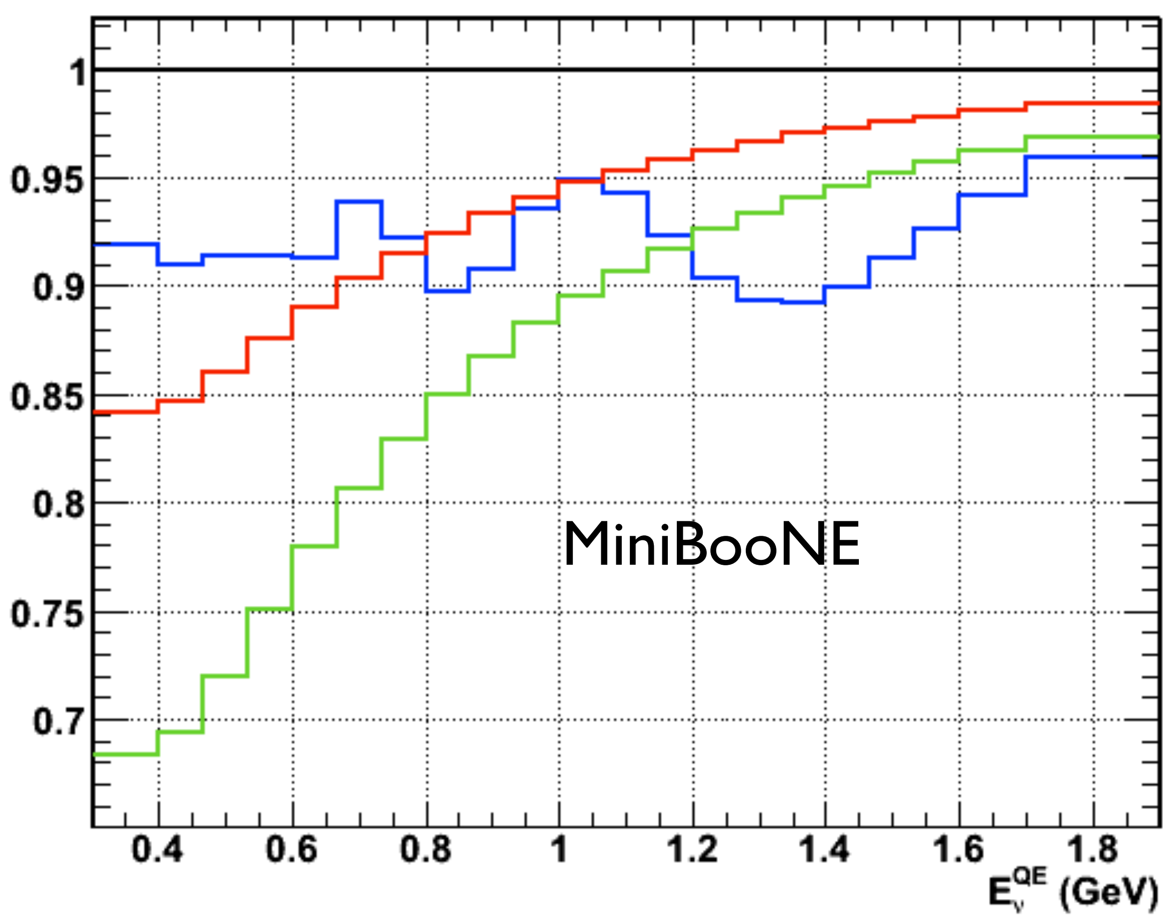




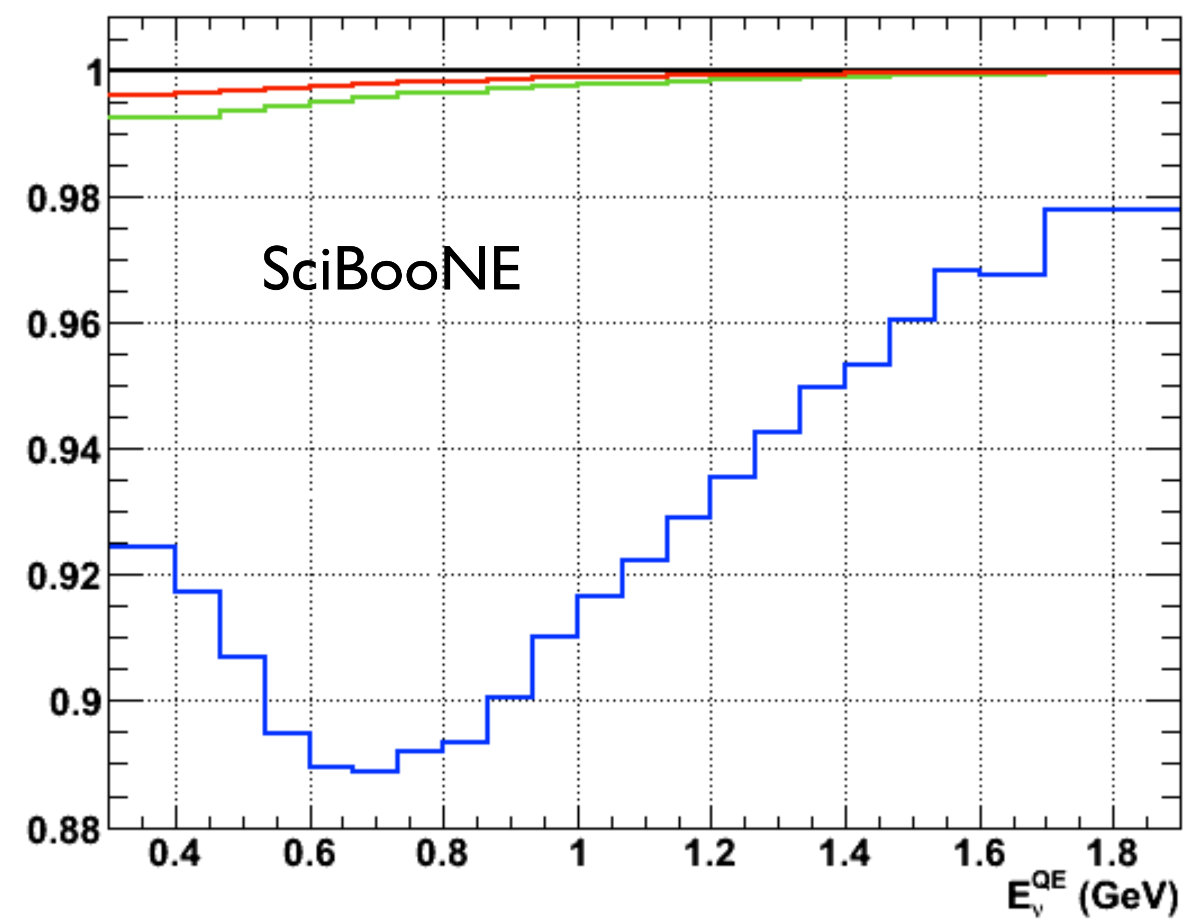
Oscillation of Simulated Events

$$P_{\bar{\nu}_\mu \to \bar{\nu}_\mu} = 1 - \sin^2 2\theta \sin^2 1.27 \frac{\Delta m^2 L}{E}$$

ratio: oscillated MC/unoscillated MC



ratio: oscillated MC/unoscillated MC



red: $\Delta m^2 = 1\ \mathrm{eV}^2,\ \sin^2(2\theta) = 0.2$

green: $\Delta m^2 = 1\ \mathrm{eV}^2,\ \sin^2(2\theta) = 0.4$

blue: $\Delta m^2 = 10\ \mathrm{eV}^2,\ \sin^2(2\theta) = 0.2$

New Data Constraints

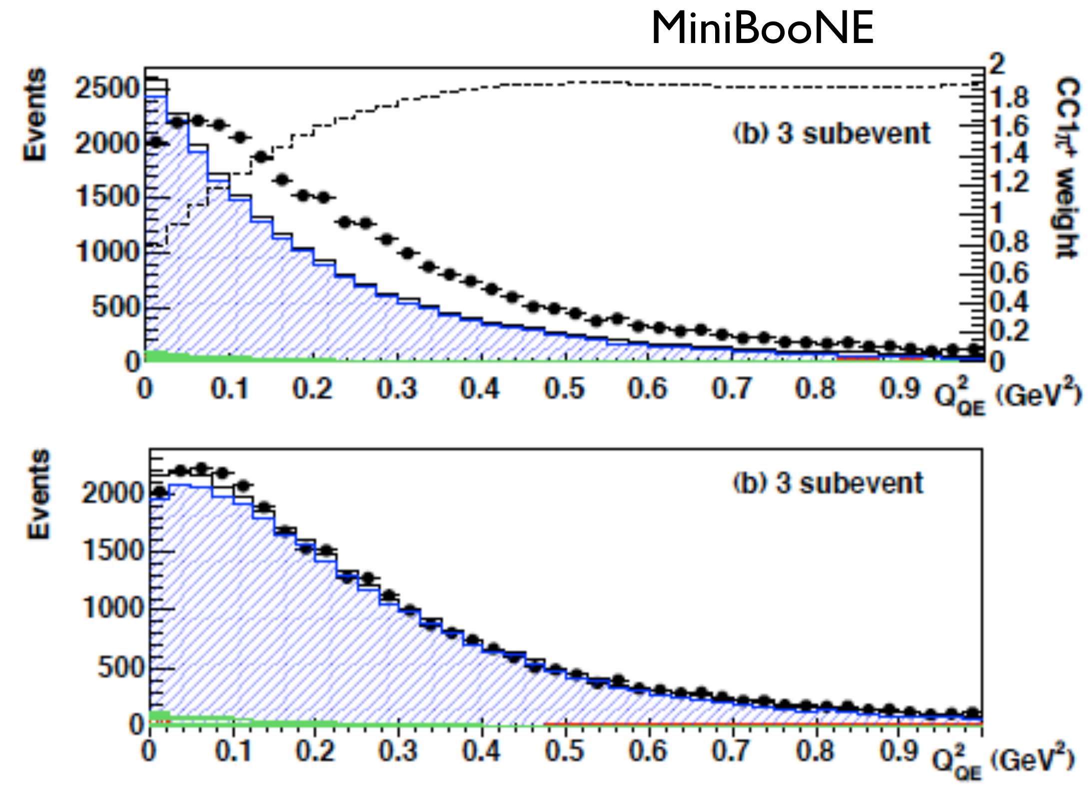
- CC1pi data constraint, as function of Q^2
- New effective axial mass and Pauli-blocking factor for CCQE events on carbon
- Normalization constraint for neutrino contamination in antineutrino beam
- Improved constraint on K+ production (not significant in this analysis)

- These internal measurements assumed no ν_μ disappearance; consistent with joint ν_μ disappearance analysis

Constraints applied to MiniBooNE and SciBooNE Monte Carlo

CC1pi Constraint

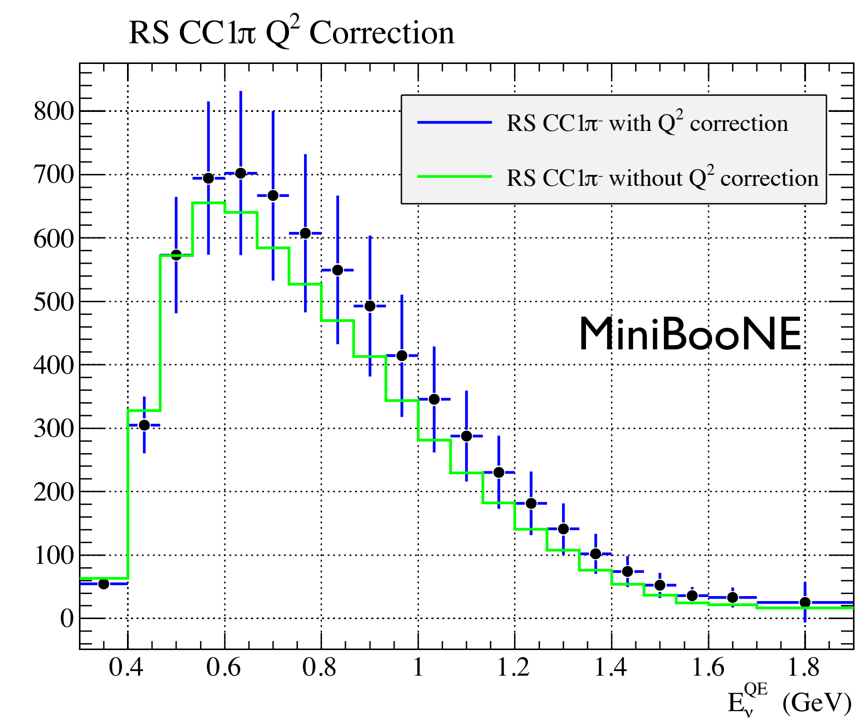
Phys. Rev. D81, 092005 (2010)



- CC1pi contamination in CCQE sample: when electron from end of pion decay chain is missed (i.e. due to muon-capture or pion absorption)
    - Has similar kinematics to full CC1pi sample

- For neutrino-mode CCQE xsec analysis, the CC1pi background in the CCQE sample was reweighted (as function of Q^2) based on a data/MC comparison in CC1pi sample
- This resulted in updated effective axial mass and Pauli blocking factor in nu-mode CCQE cross section measurement (next slide)

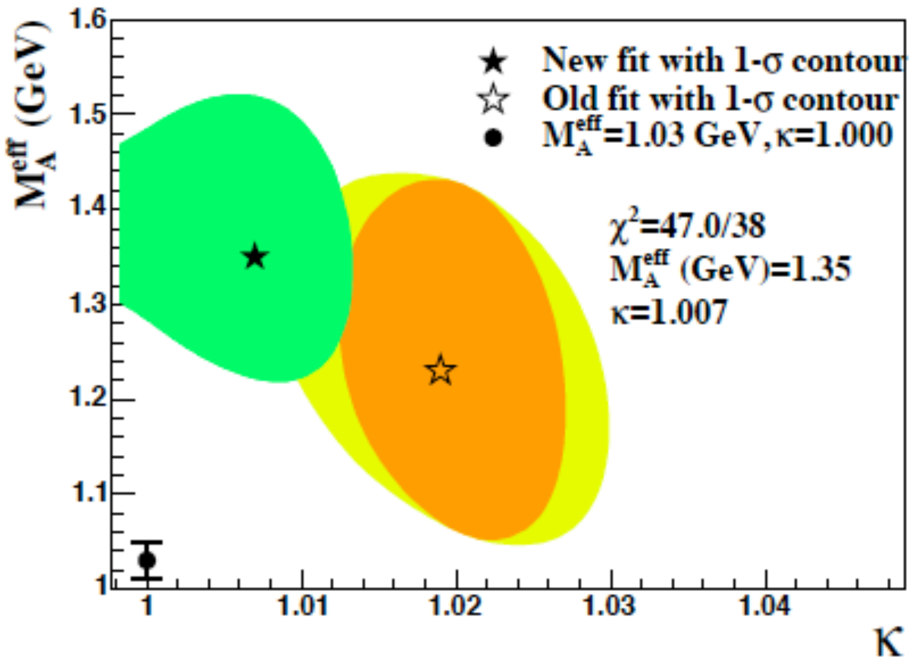
We apply this constraint to CC1pi events from neutrinos and antineutrinos



Nu-mode CCQE Cross Section Analysis

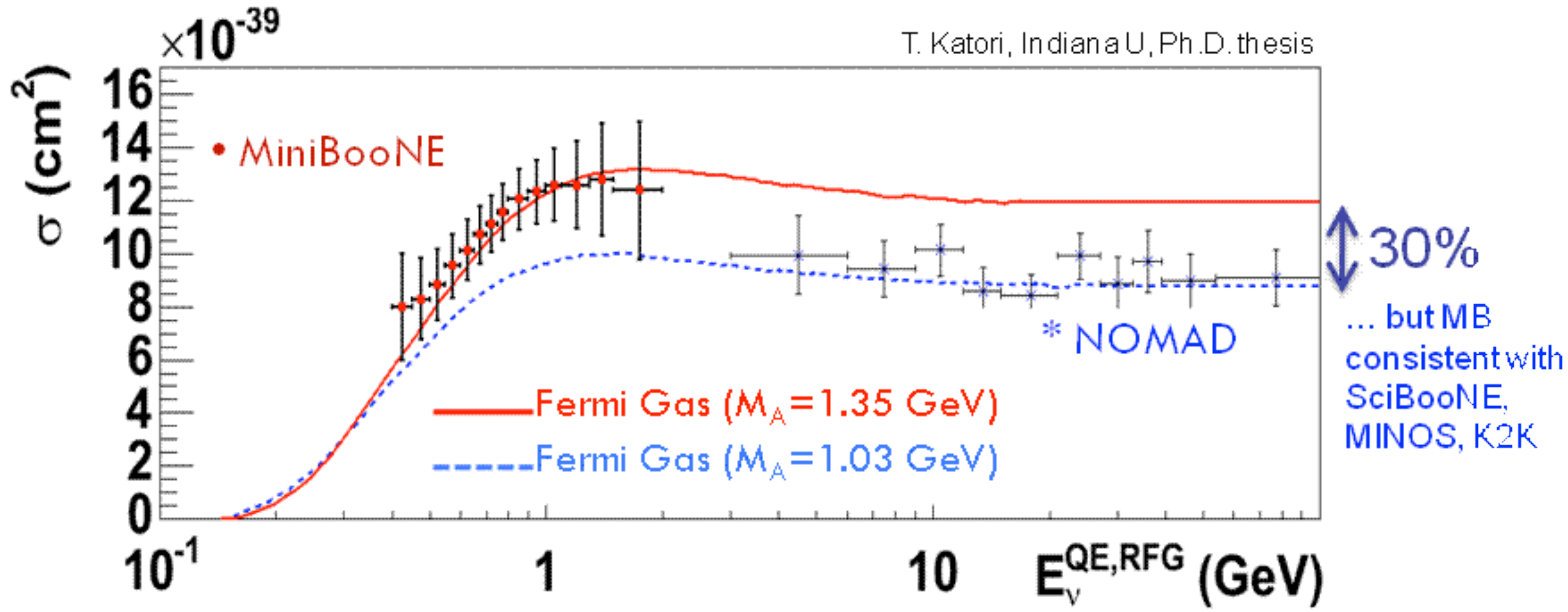
Phys. Rev. D81, 092005 (2010)

$$F_A(Q^2) = \frac{g_A}{\left(1+\frac{Q^2}{M_A^2}\right)^2} \qquad E_{lo} = \kappa\left(\sqrt{p_F^2 + M_p^2} - \omega + E_B\right)$$



$$\boxed{\begin{array}{l} M_A^{QE}(\nu,\text{Carbon}) = 1.35 \pm 0.07\ \text{GeV} \\ \kappa(\nu,\text{Carbon}) = 1.007 \pm 0.005 \end{array}}$$

Includes only statistical uncertainty on the measurement

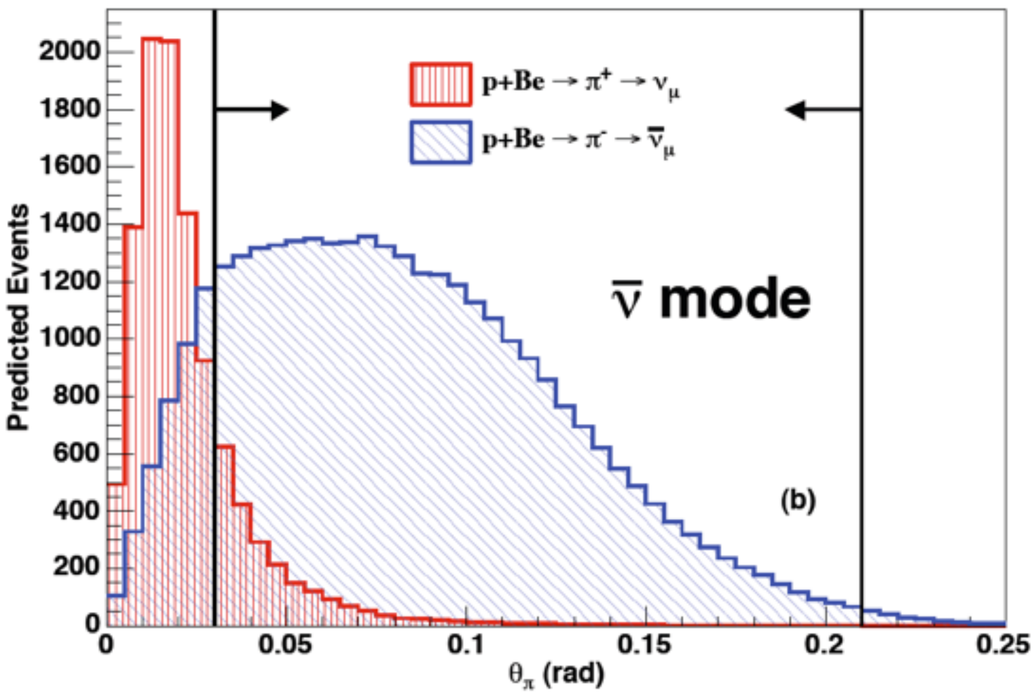


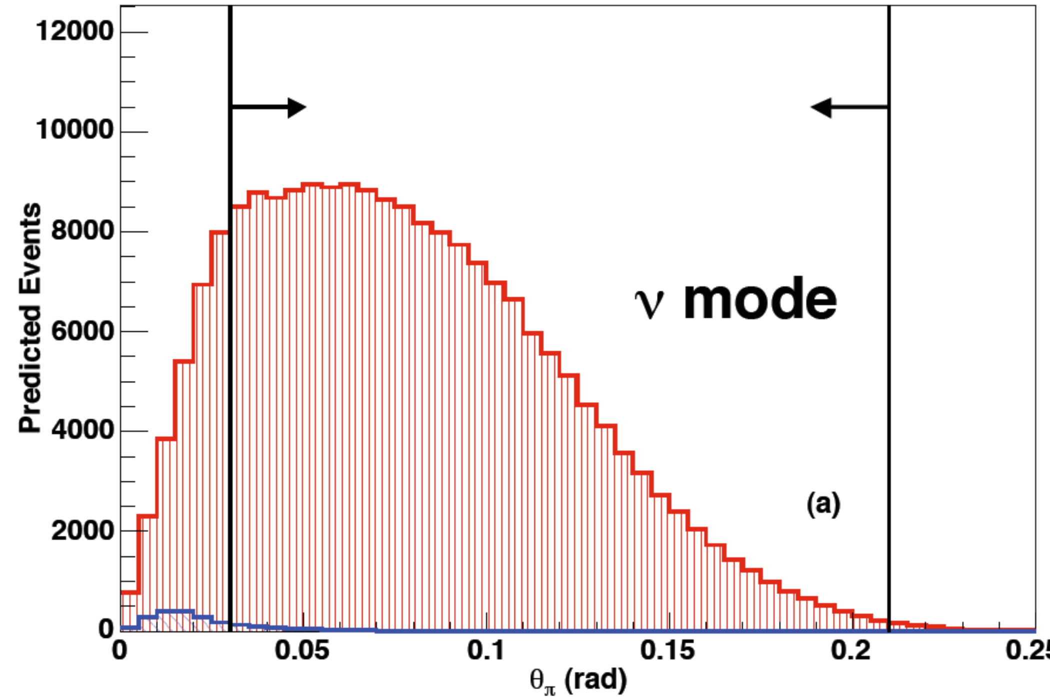
- Tension between CC exclusive measurements and theory: quasielastic, π^+, π^0
- Nuclear interactions may be the key; short-range correlations and 2-body pion-exchange currents
- Joe Carlson et al., Phys. Rev. C65, 024002 (2002); Martini et al., Phys. Rev. C80, 065001 (2009); and several others...

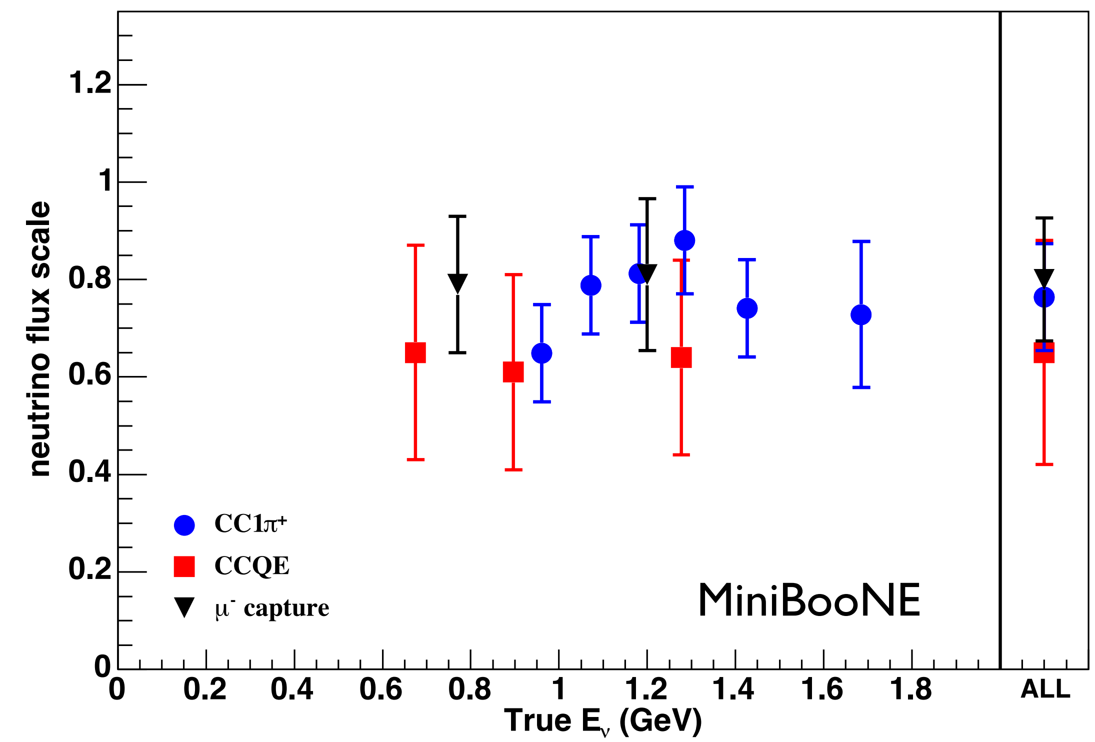
Antinu CCQE cross section measurement results coming soon!

Direct Measurement of Neutrino Contamination

Phys. Rev. D84, 072005 (2011)



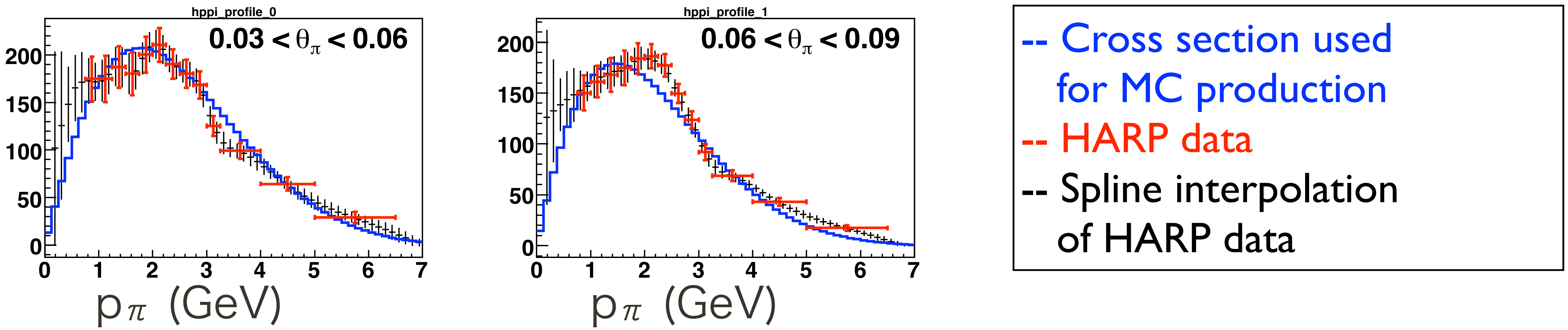




- **3 independent, complementary** measurements (arXiv: 1107.5327)
  - μ^+/μ^- angular distribution
  - μ^- capture
  - π^- absorption (CC1π^+ sample)

WS flux in antineutrino-mode rescaled by factor of 0.78, with 12.8% uncertainty

Systematic Uncertainties: Beam and Flux



New for this analysis:

- π^+ production 12.8% normalization uncertainty
- new K+ error matrix (from SciBooNE measurement; Phys. Rev. D84, 012009 (2011))

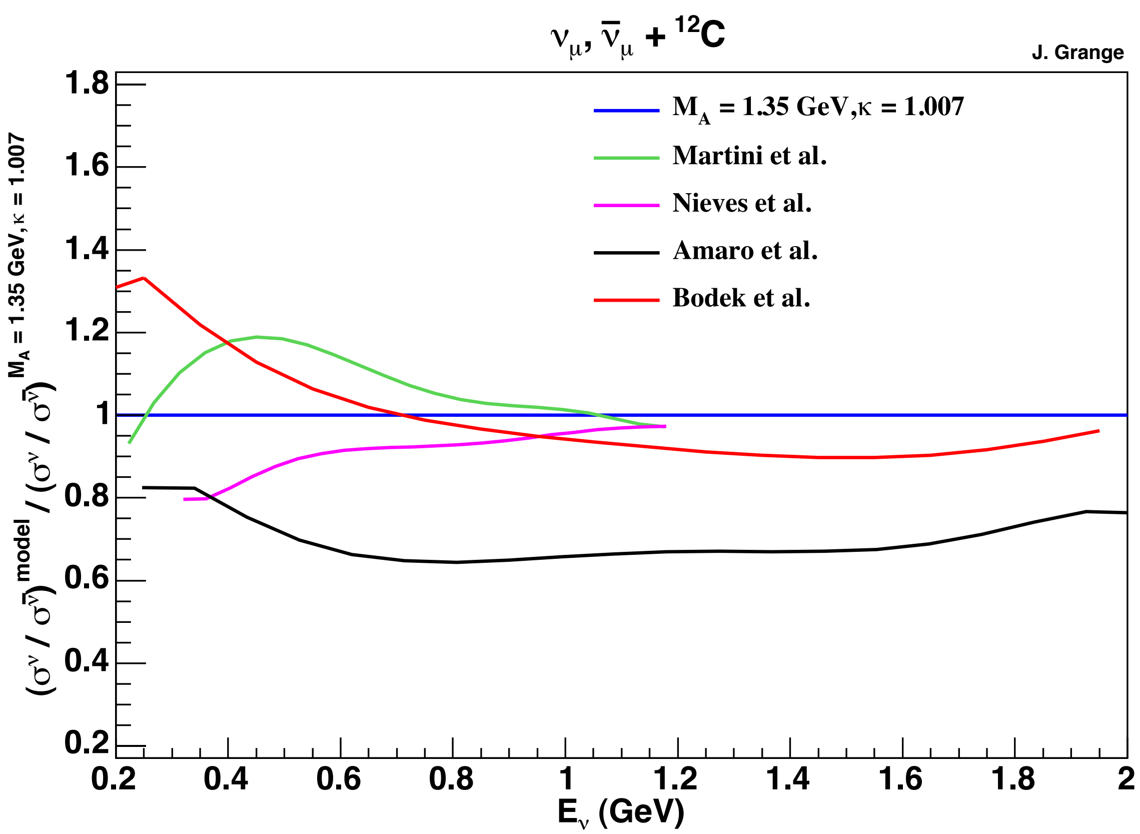
Same as prior analyses:

- π^- production: errors from spline interpolations
- K^0 production: Sanford-Wang error matrix
- K^- production: 100% normalization uncertainty
- target, horn: skin effect, horn current, cross sections, etc.

Systematic Uncertainties: Cross Section

New for this analysis:

- M_A(CCQE,Carbon)=1.35±0.07 GeV
  - κ=1.007±0.005
- M_A(CCQE,Hydrogen)=1.014±0.014 GeV (J. Phys. Conf. Ser. 110, 082004 (2008))
- Additional 40% normalization error allowed for anti-nu CCQE on carbon



Same as prior analyses:

- M_A(CC Resonant 1π)=1.1±0.275 GeV *
- M_A(CC Coherent 1π)=1.03±0.275 GeV *
- M_A(multi-π)=1.3±0.52 GeV
- Additional 10% uncertainty on all CCQE interactions on carbon (covers residual discrepancy between data/MC in nu-mode measurement)
- Additional 10% uncertainty on all antineutrino interactions on carbon to account for possible differences in nuclear effects between nu and anti-nu scattering not accounted for in the Relativistic Fermi Gas model

- * For <u>neutrino</u> resonant and coherent 1π events, the flux and xsec uncertainty are both constrained by the 12.8% normalization uncertainty

Systematic Uncertainties: Detectors

- Same as previous MiniBooNE and SciBooNE analyses:
  - Electronics
  - Optical Model
  - Target Density
  - etc.
- These uncertainties don't cancel; as a result they remain a systematic limitation

Total Uncertainty

Fractional Uncertainty

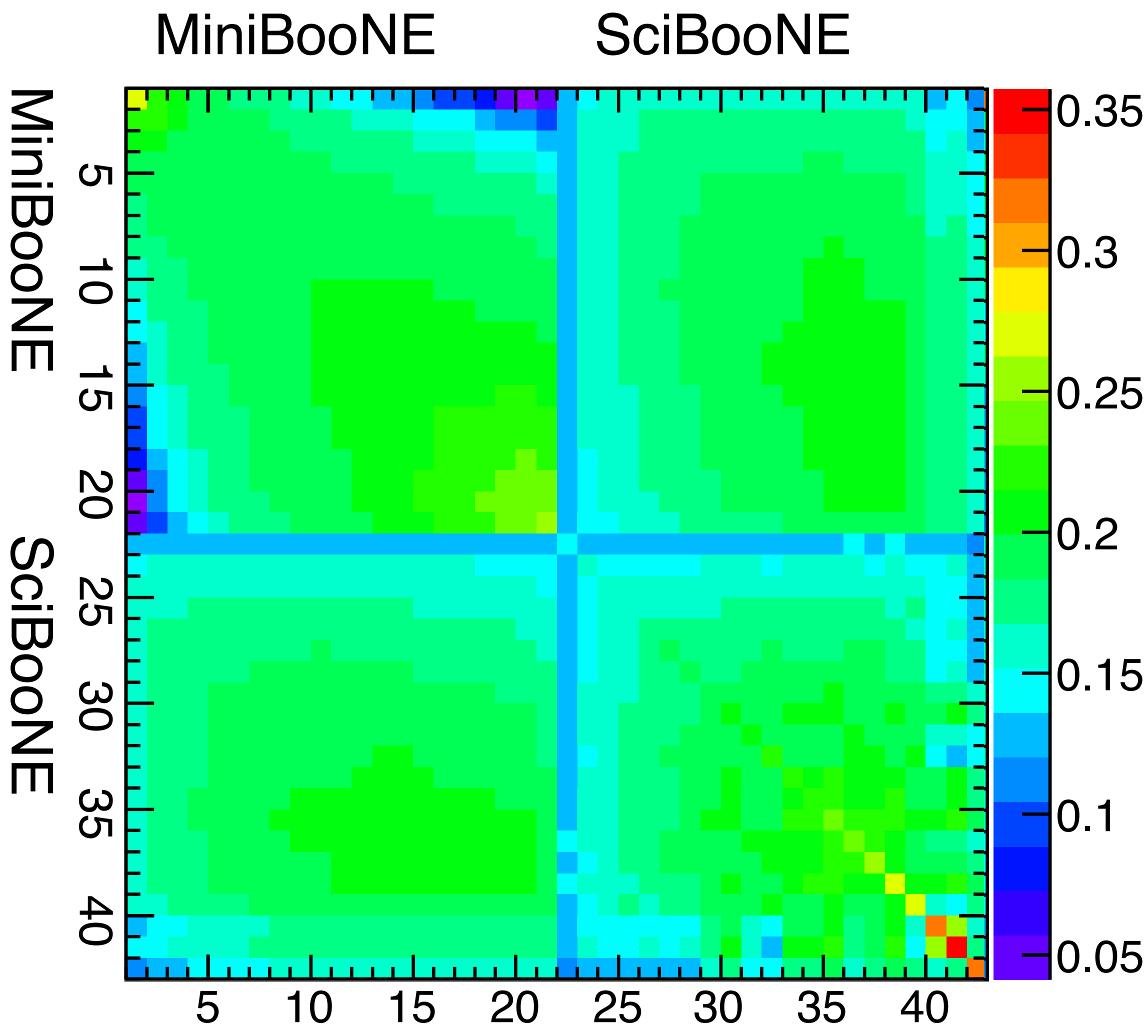


FIG. 10. Bin-wise square root of the total (statistical and systematic errors combined) fractional error matrix $\sqrt{\hat{M}_{ij}} = \sqrt{M_{ij}}/\sqrt{N_i N_j}$, where M_{ij} is the total error matrix and N_i (N_j) is the MC prediction for reconstructed antineutrino energy bin i (j). Bins 1 through 21 are MiniBooNE, bins 22 through 42 are SciBooNE.

Correlations

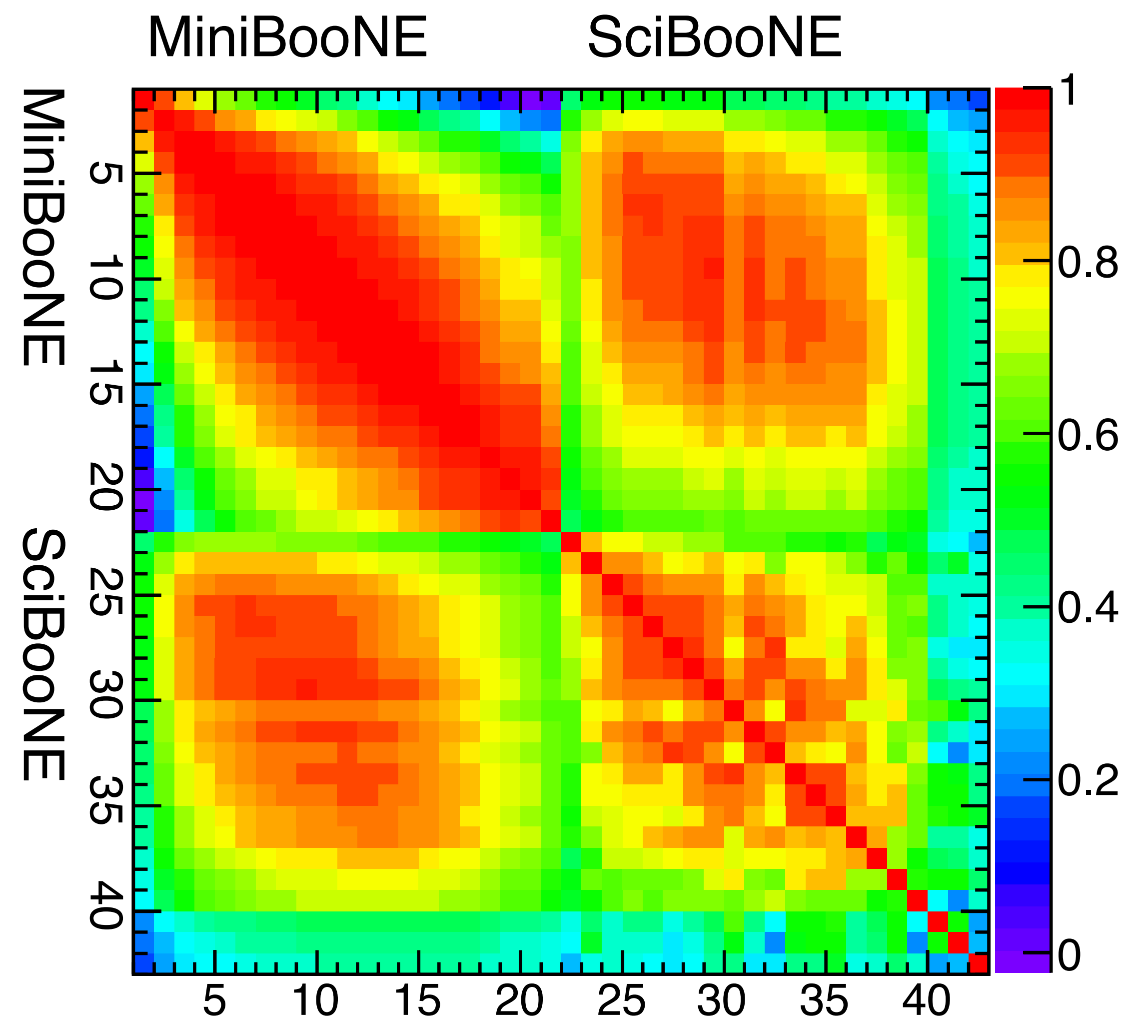
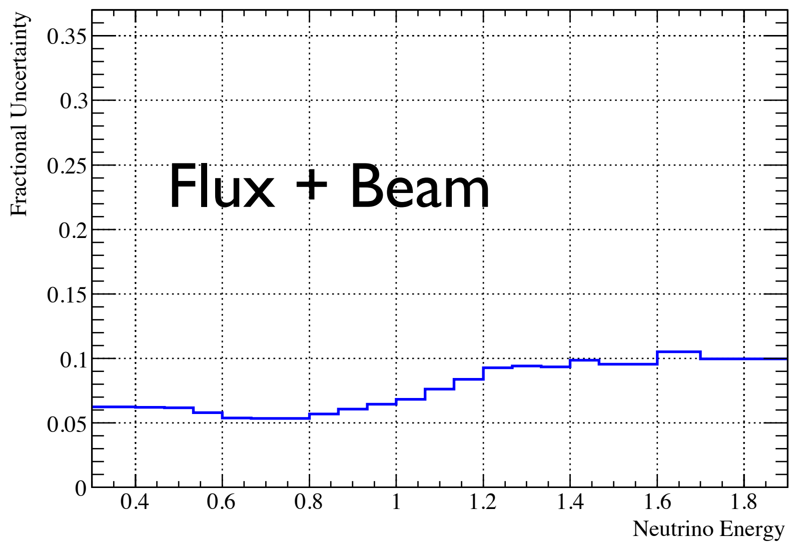
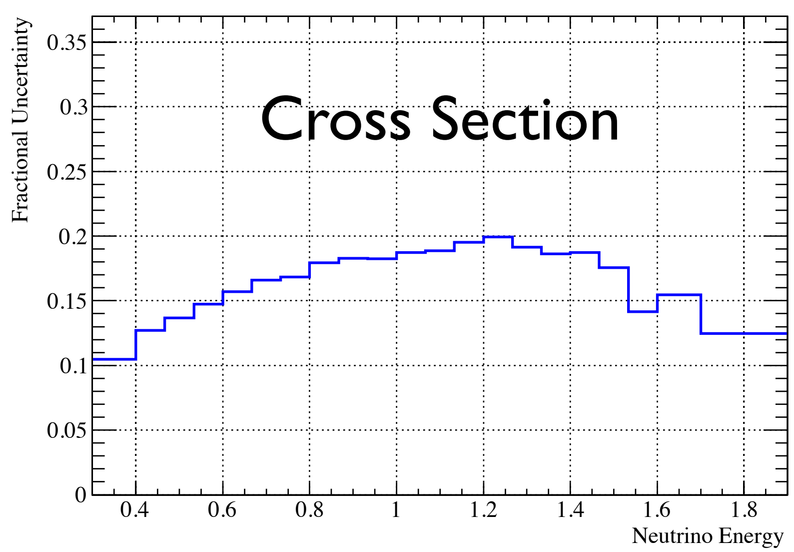
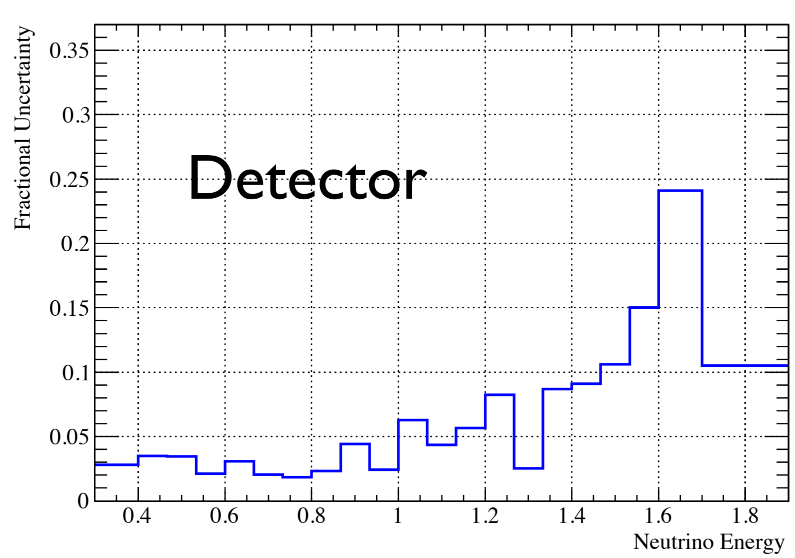


FIG. 11. Correlation coefficients of the total (statistical and systematic errors combined) error matrix ($\rho_{ij} = M_{ij}/(\sigma_{ii}\sigma_{jj})$). Bins 1 through 21 are MiniBooNE, bins 22 through 42 are SciBooNE. No bins are anti-correlated.

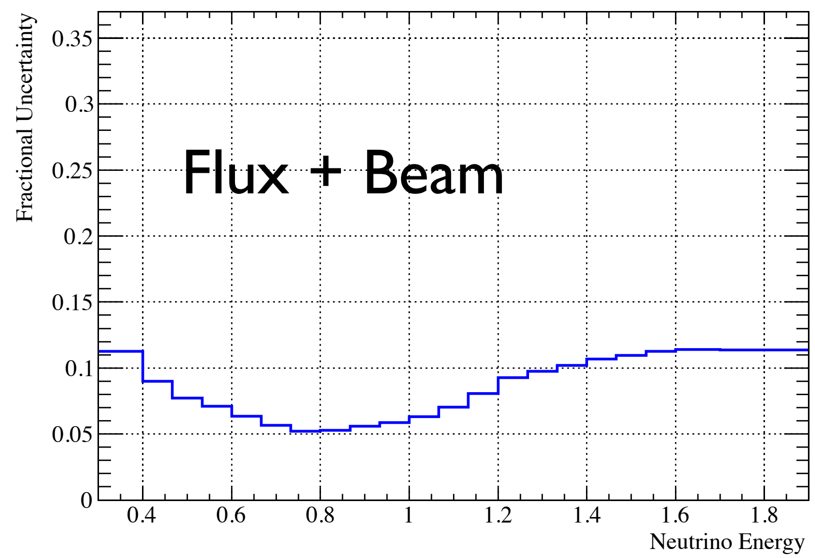
SciBooNE

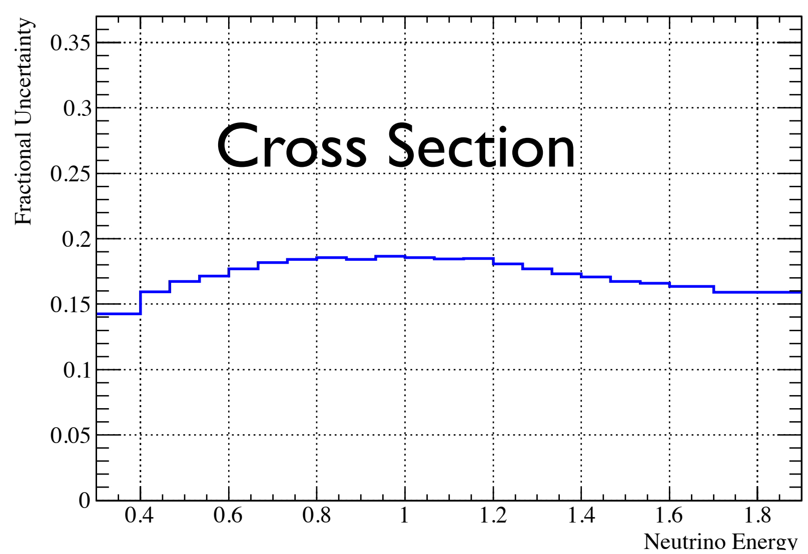


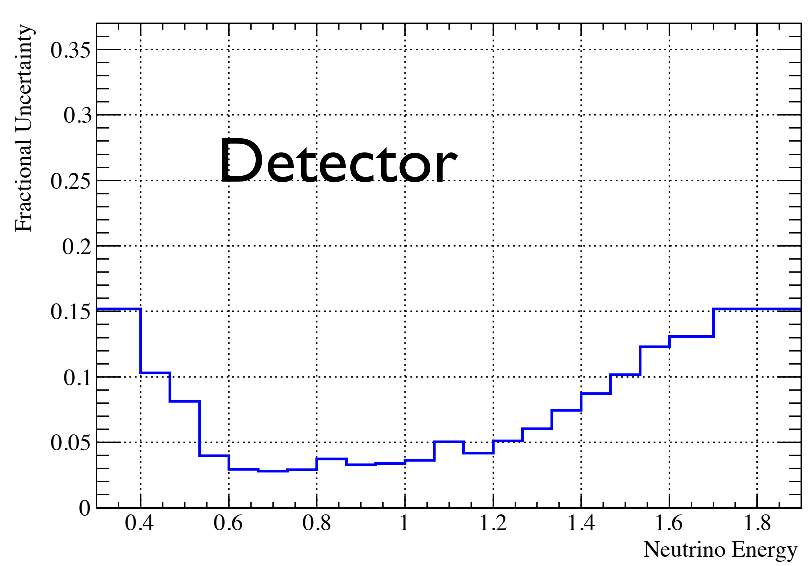




MiniBooNE

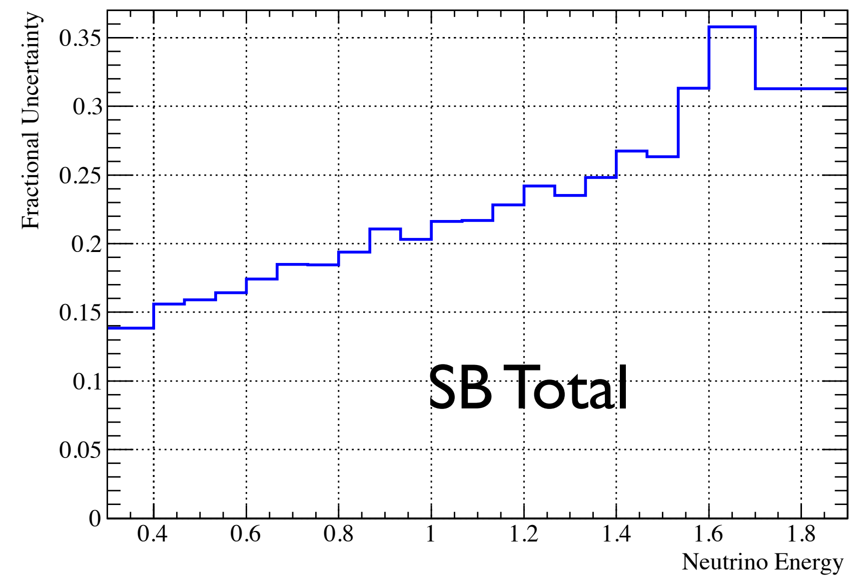


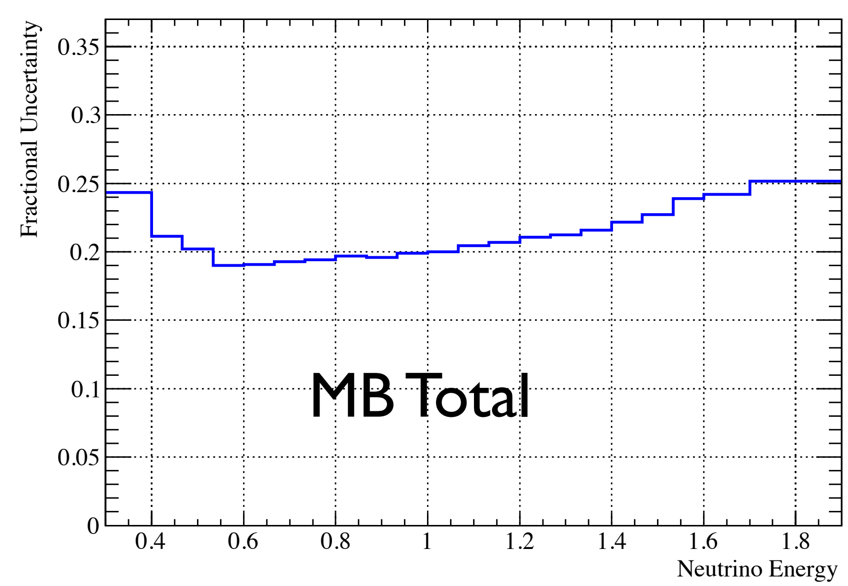




Fractional Uncertainties

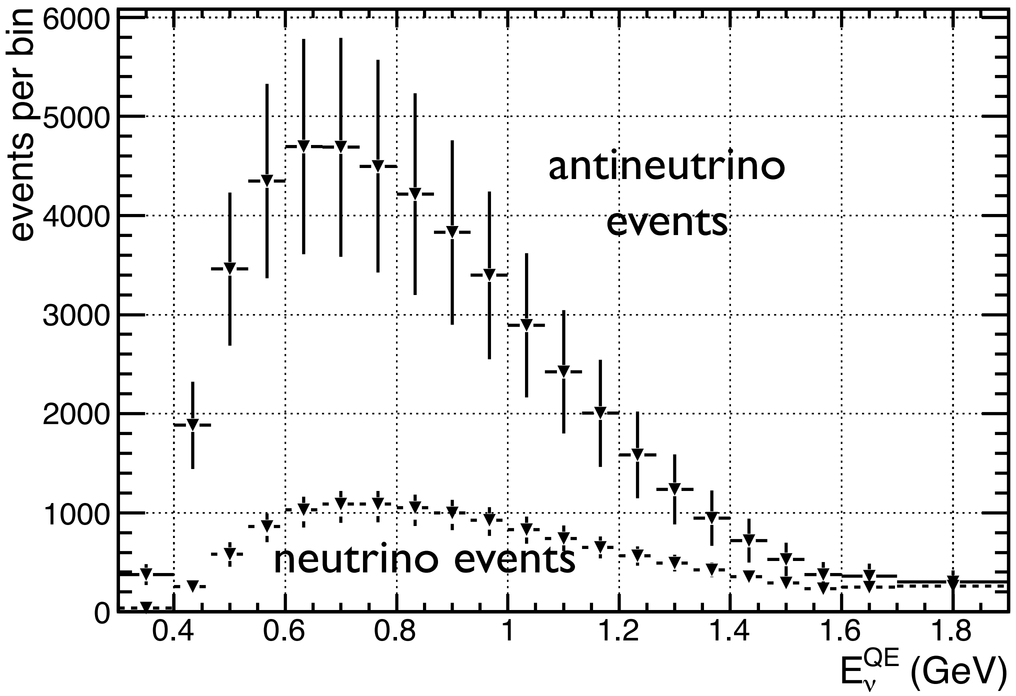
$$\sqrt{\hat{M}_{ii}} = \sigma_{ii} / x_{ii}$$



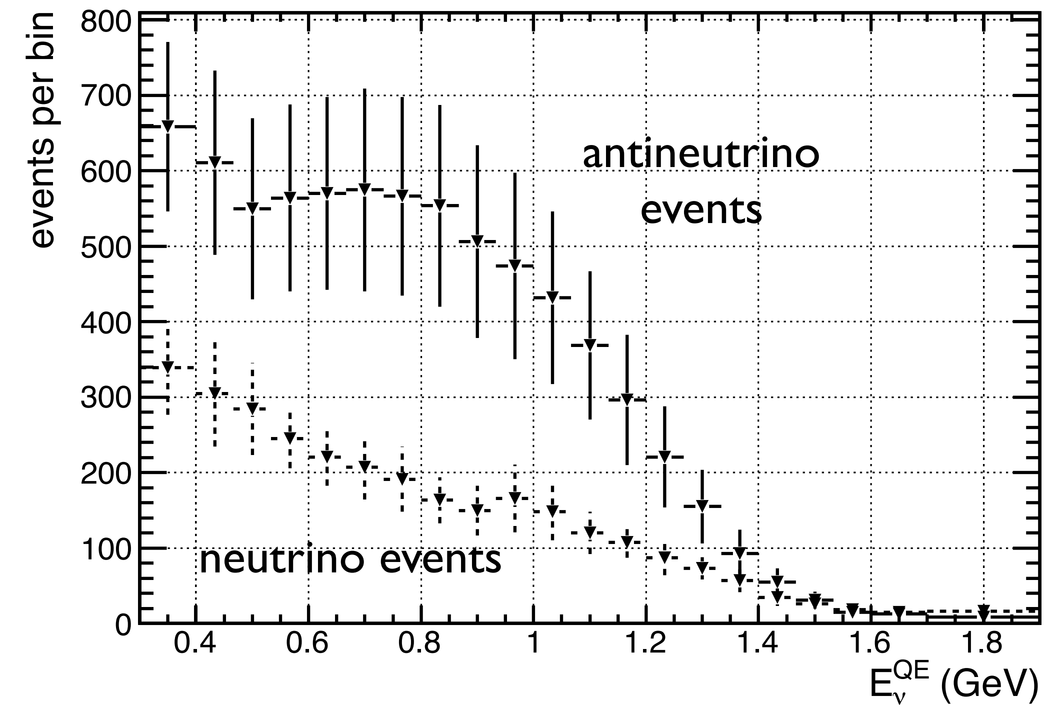


Data to MC Comparison

MiniBooNE RS and WS predictions with uncertainty

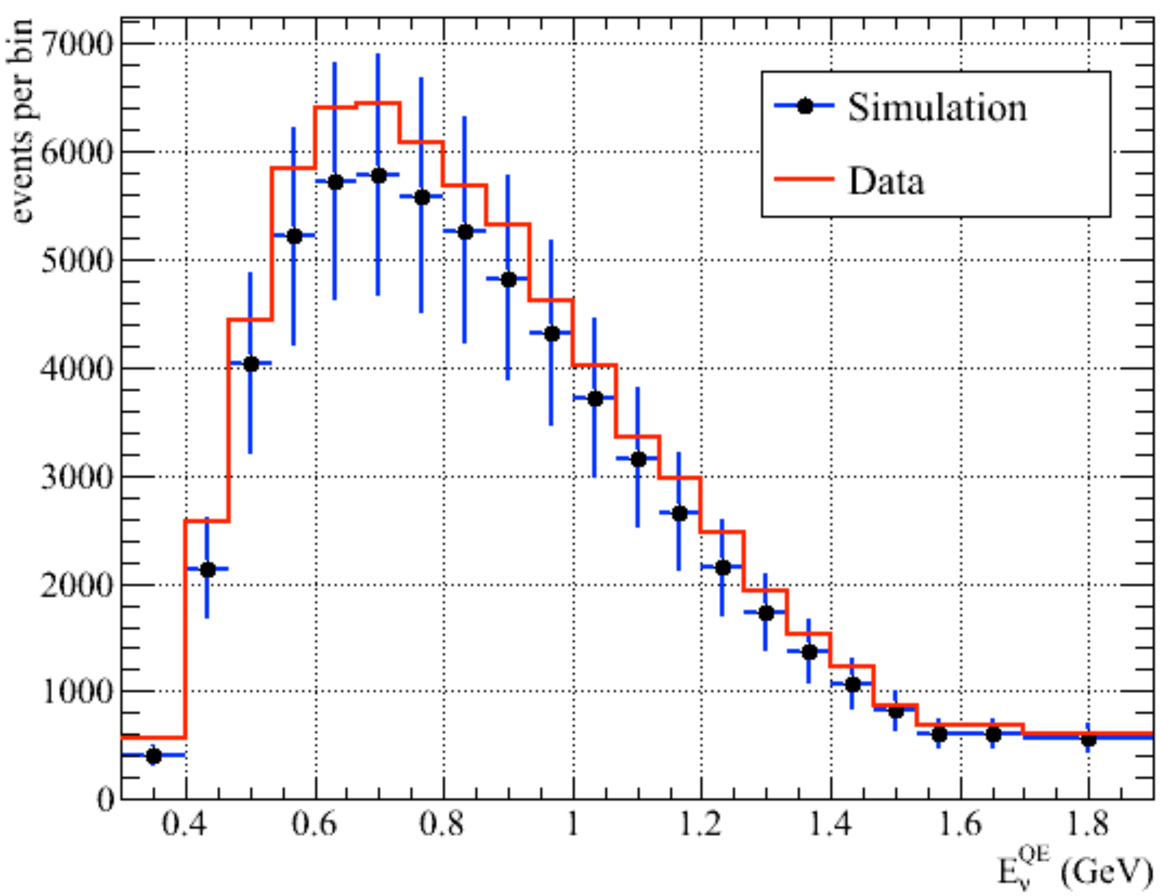


SciBooNE RS and WS predictions with uncertainty

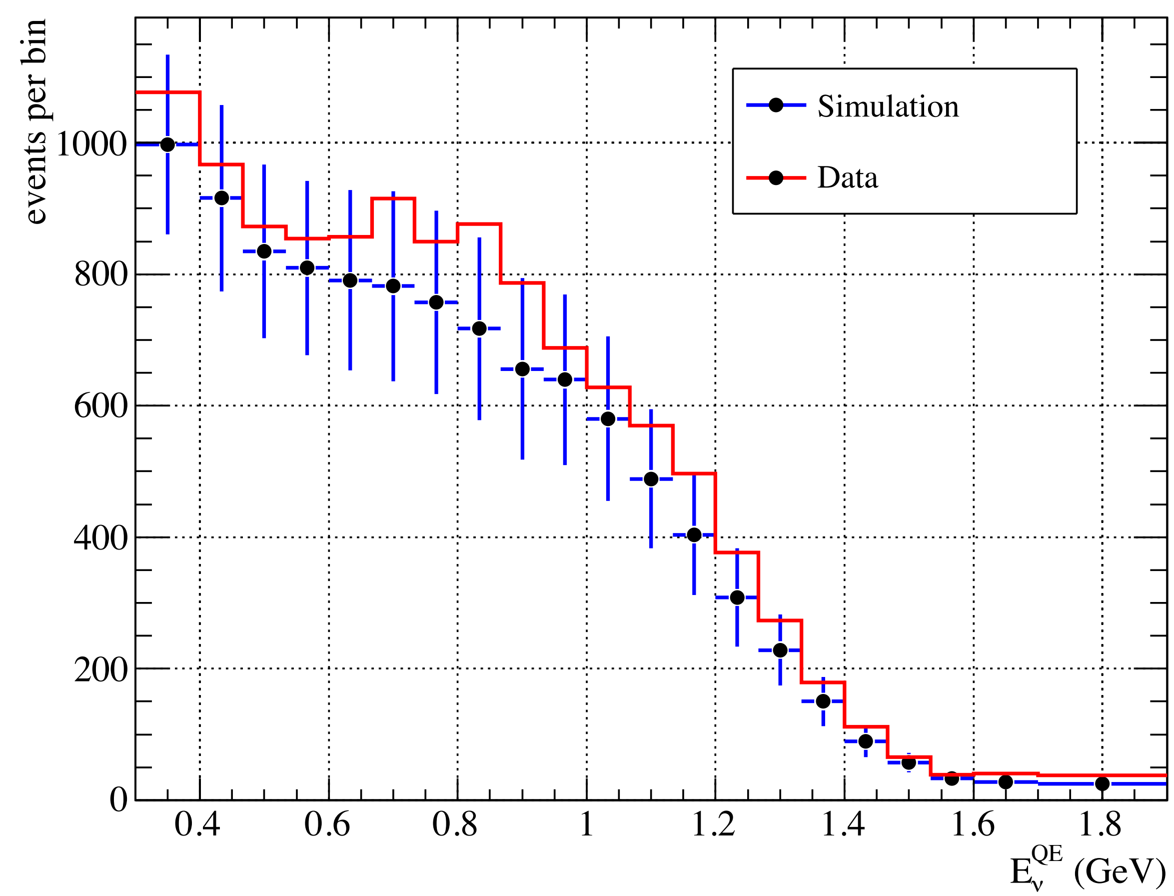


MiniBooNE

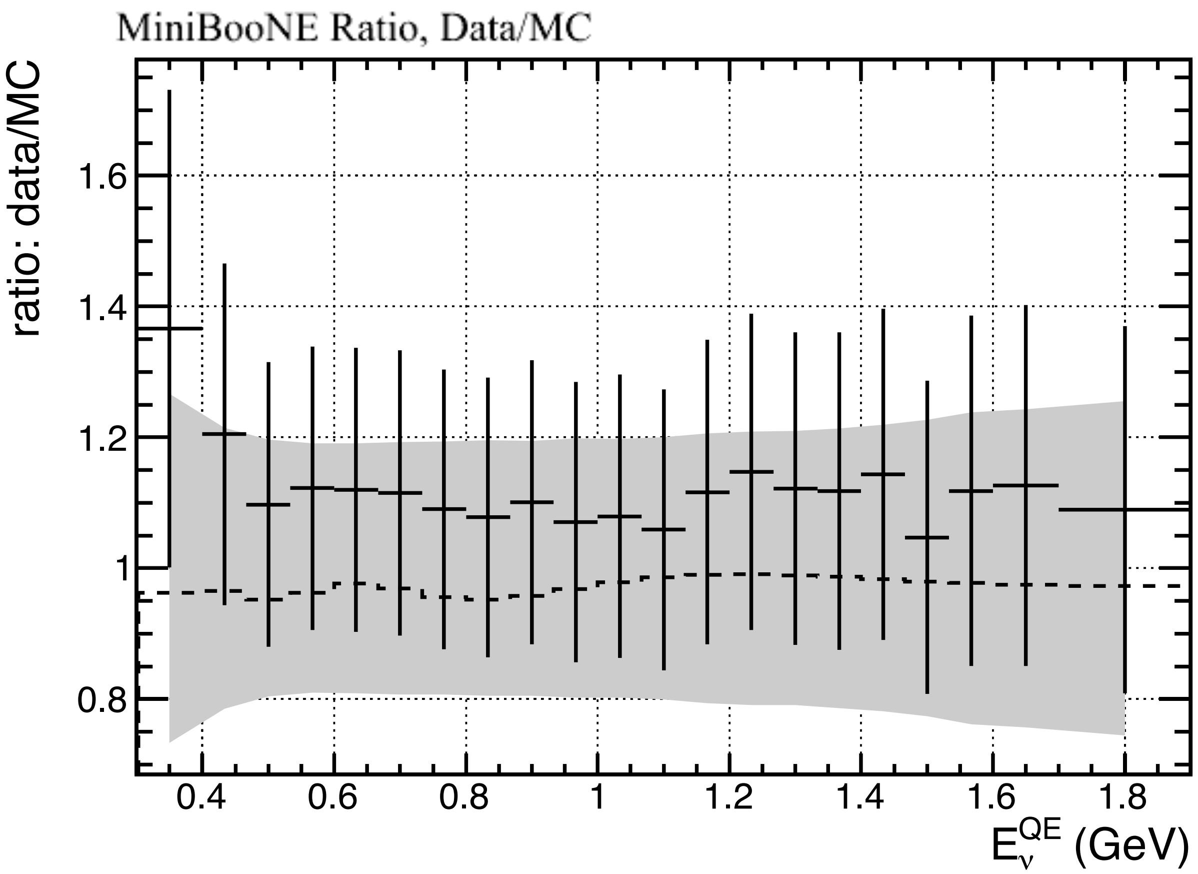
Reconstructed Energy Distribution

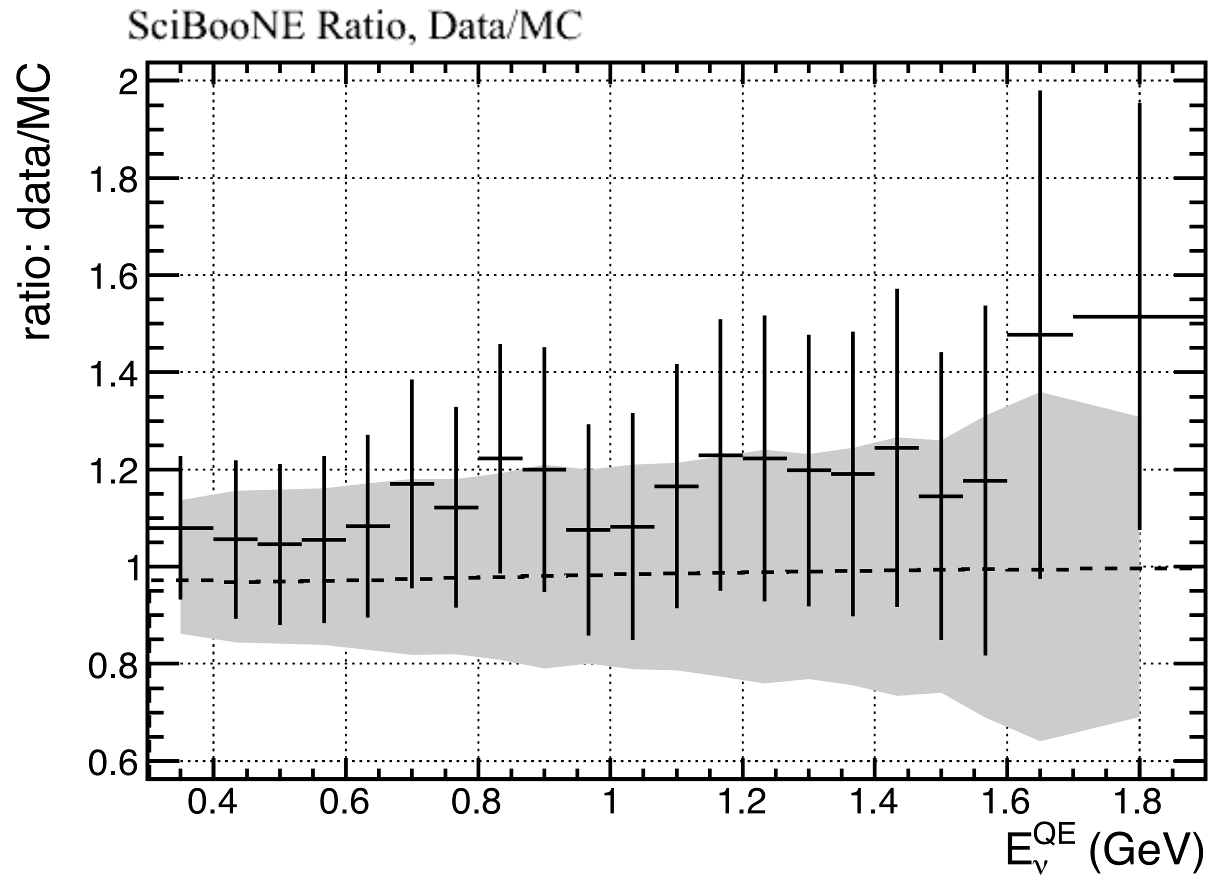


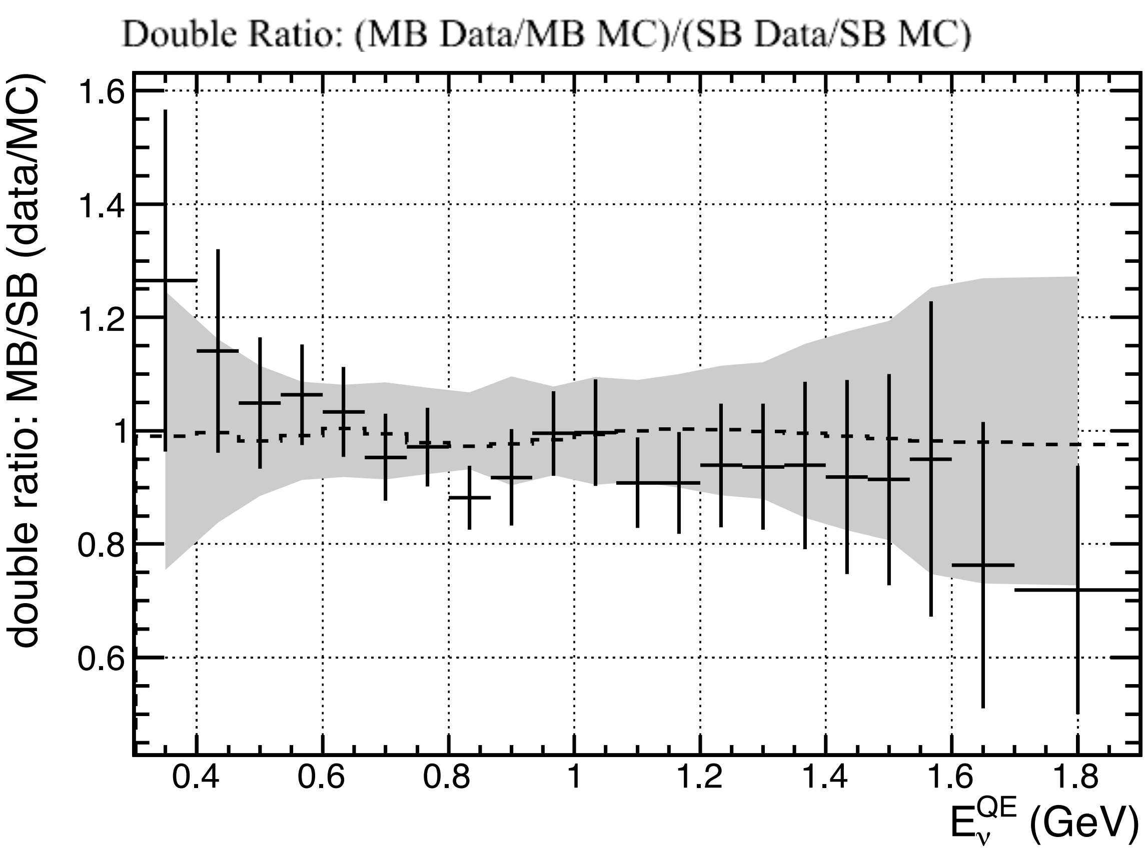
SciBooNE Reconstructed Energy Distribution



Data to MC Ratios

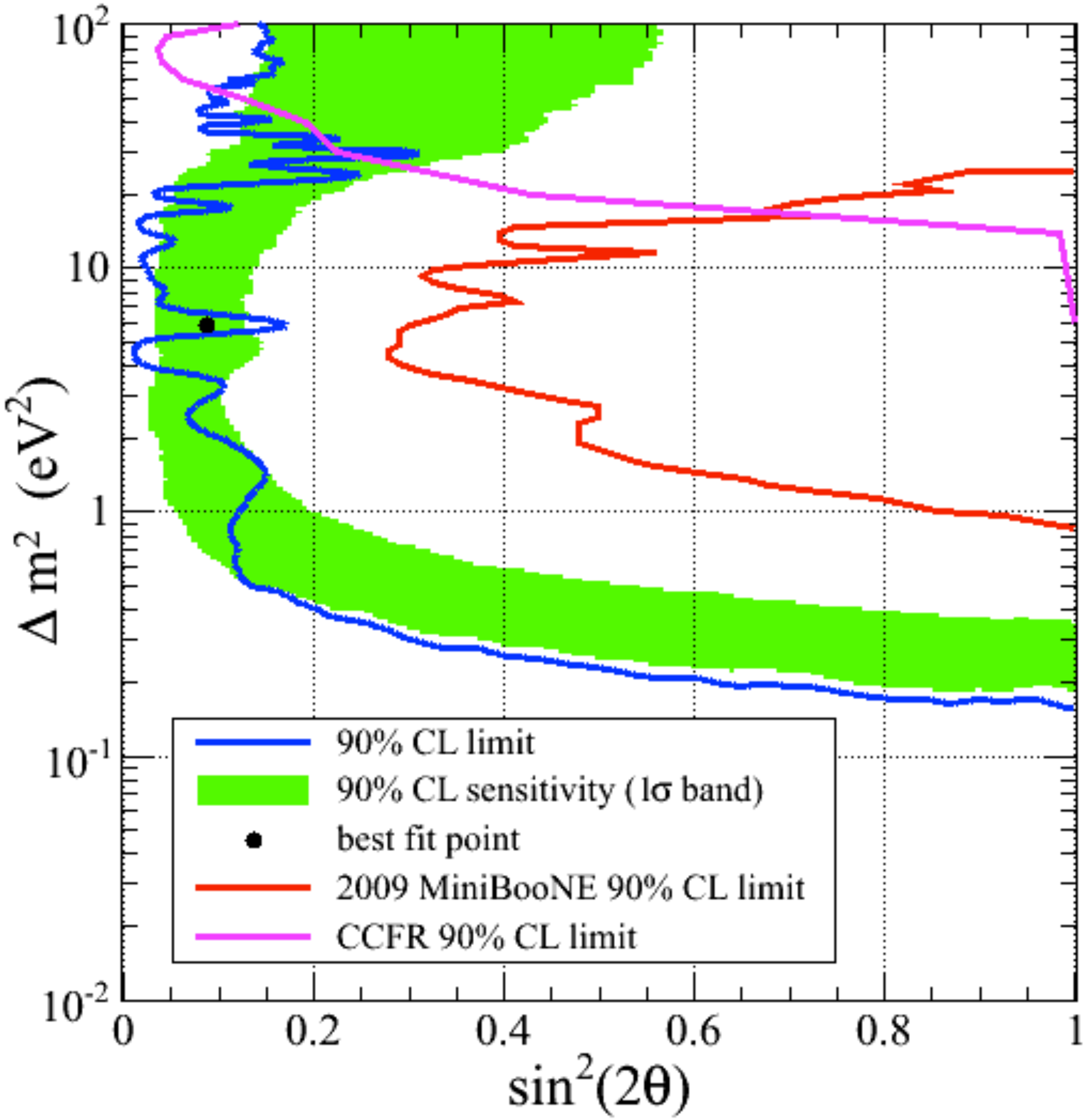






- Shaded regions are variations from fake data tests with no oscillations
- Dashed lines are “best fit MC” divided by “unoscillated MC”
- Double ratio plot gives sense for how some systematic uncertainties cancel

Results



Consistent with no disappearance

Best fit point: $\Delta m^2 = 5.9$ eV^2, $\sin^2 2\theta = 0.086$

$\chi^2 = 40.0$ (probability 47.1%) at the best fit point

$\chi^2 = 43.5$ (probability 41.2%) for the null hypothesis

With $\Delta\chi^2 = 3.5$, null is excluded at 81.9% confidence level

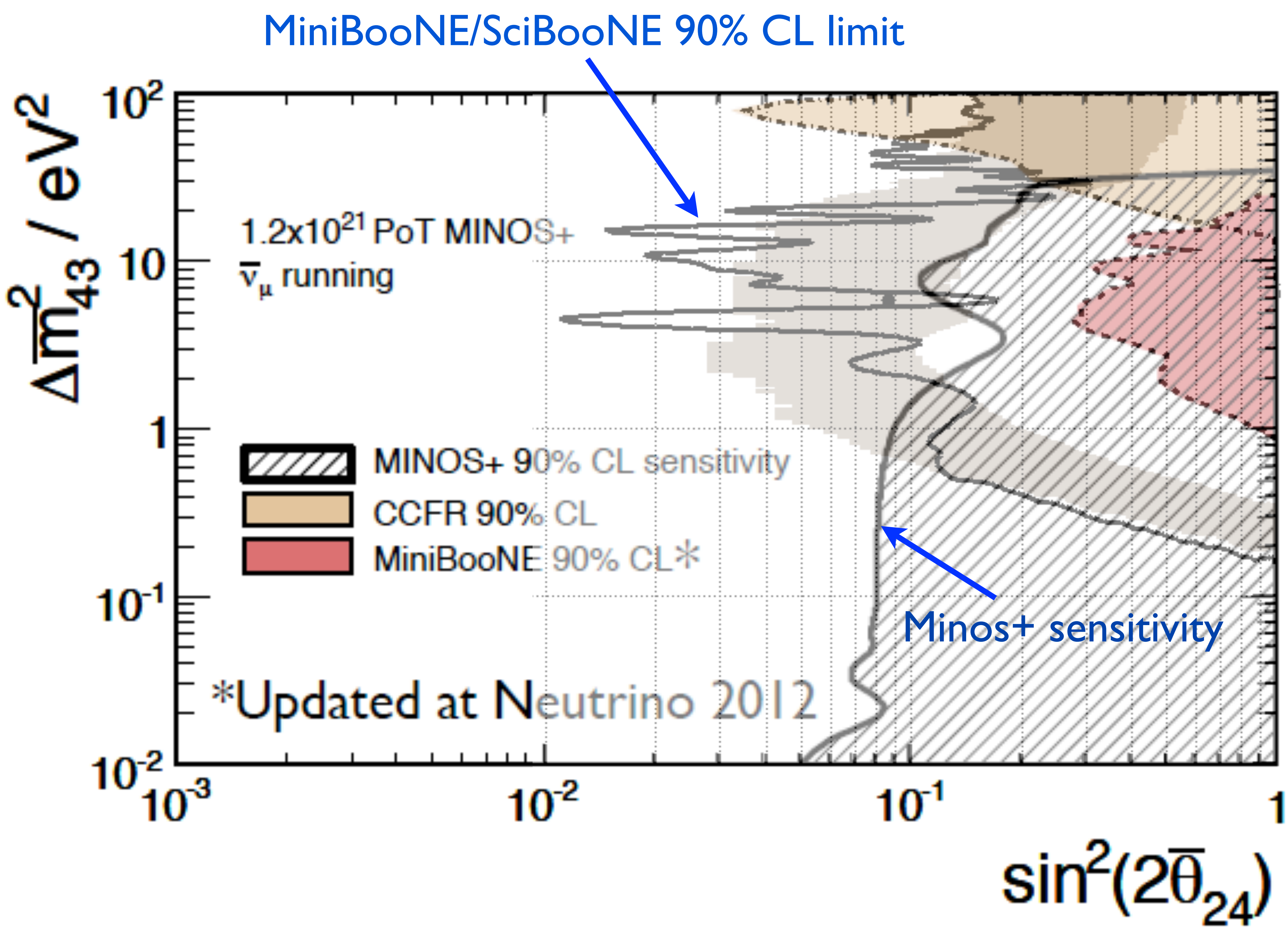
Probabilities are based on fake data studies (Feldman-Cousins statistical analysis)

arXiv:1208.0322 (submitted to Phys. Rev. D)

Improvements in Sensitivity Relative to 2009 Analysis

- Main factors contributing to improved sensitivity:
  - more MiniBooNE data (approx 3 times as much as 2009 analysis)
  - tighter constraints on neutrino CCQE and CC1pi events
  - differences in analysis methodology:
    - DeltaChi^2 test statistic rather than Chi^2; 2009 analysis was a shape-only fit; uncertainties for RS and WS events are handled separately in new analysis; the error matrix is updated based on Monte Carlo predictions as parameter space is scanned, etc.
  - addition of SciBooNE data

Minos+ Estimated Sensitivity



Summary

- Dramatic improvement in sensitivity to muon antineutrino disappearance by bootstrapping off of internal, neutrino mode measurements, and including data from SciBooNE
- Results are consistent with no $\bar{\nu}_\mu$ disappearance; and with previous MiniBooNE/SciBooNE ν_μ disappearance analysis
- Leaves some room for sterile neutrino models that attempt to account for LSND and MiniBooNE appearance data, but closing in on the 3+1 model's phase space; (3+2 and 3+3 models will have different limits)
- Modest gain in sensitivity may be possible by combining neutrino and antineutrino-mode data; however this will require resolution of multinucleon knockout problem
- Data Release: http://www-sciboone.fnal.gov/data_release/joint_numubar_disap/